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Assessment of Municipal Solid Waste Energy Recovery Technologies

Final Report

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Assessment of Municipal Solid Waste Energy Recovery Technologies
Final Report

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Acronyms

AD	anaerobic digestion
BTU	British thermal unit
C	Celsius
CISWI	commercial and solid waste incinerators
CO	carbon monoxide
DST	decision support tool
GHG	greenhouse gas
GWP	global warming potential
HDPE	high density polyethylene
IGCC	integrated gasification combined cycle
kg	kilogram
L	liter
LCA	life cycle assessment
LCI	life cycle inventory
LDPE	low density polyethylene
LMOP	Landfill Methane Outreach Program
MACT	Maximum Achievable Control Technology
MJ	mega joule
MRF	materials recovery facility
MSW	municipal solid waste
MW	megawatt
NAAQS	National Ambient Air Quality Standards
NHSM	Non-Hazardous Secondary Material
NNSR	Nonattainment New Source Review
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
PET	polyethylene terephthalate
PM	particulate matter
PP	polypropylene
PS	polystyrene
PSD	Prevention of Significant Deterioration
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RDF	refuse-derived fuel
SHC	Sustainable and Healthy Communities
SWOLF	Solid Waste Optimization Life-cycle Framework
Syncrude	synthetic petroleum or synthesis petroleum
Syngas	synthetic gas or synthesis gas
Ton	2,000 pounds
Tonne	Metric ton (2,204.6 pounds)
VOC	volatile organic compound

WRRF	Water Resource Recovery Facilities
WTE	waste-to-energy
WWTP	waste-water treatment plant

Acknowledgements

This report was prepared to provide an understanding of options for technologies to “manage” plastics, glass, metals, paper, food waste, and other materials that comprise municipal solid waste. This has been a challenging topic due to many of the emerging technologies not being successful and currently not in operation. Comparing emerging technologies with established technologies is difficult primarily due to the lack of long-term performance data. Using life-cycle methodology and all available data, we compared emerging technologies for materials management versus established technologies (i.e., combustion and landfilling).

As a project team, we met often to discuss the results and how best to communicate including the uncertainties. We want to acknowledge the contributions of the RESES team – Carol Staniec (Region 5), and Steve Wall (Region 9) and Charles Swanson (Region 9). Carol Staniec (Region 5) provided her expertise on anaerobic digesters and their deployment in the U.S. Charles Swanson (Region 9) conducted the EJSCREEN evaluation working to document potential environmental justice concerns. Steve Wall (Region 9) contributed to the landfill section and the explanation of how EPA defines waste as a fuel. We also acknowledge the contributions of the external reviewers, quality assurance review, peer reviews and administrative review.

Disclaimer

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Foreword

The US Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The Center for Environmental Solutions and Emergency Response (CESER) within the Office of Research and Development (ORD) conducts applied, stakeholder-driven research and provides responsive technical support to help solve the Nation’s environmental challenges. The Center’s research focuses on innovative approaches to address environmental challenges associated with the built environment. We develop technologies and decision-support tools to help safeguard public water systems and groundwater, guide sustainable materials management, remediate sites from traditional contamination sources and emerging environmental stressors, and address potential threats from terrorism and natural disasters. CESER collaborates with both public and private sector partners to foster technologies that improve the effectiveness and reduce the cost of compliance, while anticipating emerging problems. We provide technical support to EPA regions and programs, states, tribal nations, and federal partners, and serve as the interagency liaison for EPA in homeland security research and technology. The Center is a leader in providing scientific solutions to protect human health and the environment.

Gregory Sayles, Director
Center for Environmental Solutions and Emergency Response

Executive Summary

Sustainable materials management is a systemic approach to using and reusing materials more productively over their entire life cycles. It represents a change in how our society thinks about the use of natural resources and environmental protection.

The United States Environmental Protection Agency (EPA) has established a Non-Hazardous Materials and Waste Management Hierarchy[1], which prioritizes and ranks the various management strategies from most to least environmentally preferred. The hierarchy places emphasis on reducing, reusing, and recycling as key to sustainable materials management. Some communities are also interested in assessing waste-to-energy alternatives for non-recyclable material, contaminated recovered materials that don't meet specifications for recycling, and residue streams that are not recycled due to market limitations.

A conventional waste-to-energy (WTE) facility accepts unprocessed municipal solid waste (MSW) which is burned in a large combustion unit to generate electricity or utilized in a combined heat and power system. They further recover ferrous and non-ferrous materials that is sold into the recycle market. In the US waste-to-energy facilities with energy recovery began in the early 1980s. EPA (2018) reports 13% of MSW was combusted in 2015, down from a high of 17% in 1996. There are 73[2] operating WTE facilities in the US, down from 112 in 1997. In contrast, WTE is more prevalent in Europe. Food waste and other biodegradable waste are not allowed to be landfilled in Europe. Therefore, more digestion of food waste and other recovery technologies are more widely used in Europe resulting in less carbon emissions per ton of waste than how the materials are managed in the U.S. As long as the cost of landfills do not consider the environmental externalities such as increased carbon emissions per ton of waste, the technologies described in this report will have a more difficult time being cost competitive. (Thorneloe, 2019)[3] ; (Kaplan, et al., 2009)[4]

Waste "conversion technologies" such as gasification and pyrolysis are less established in the US and the world. These technologies differ from conventional WTE in that they do not directly combust MSW. Instead they convert MSW feedstock via partial-oxygen or oxygen-absent thermochemical. The resulting gases can be combusted to produce electricity or further processed into a liquid fuel or chemical commodity product. Such conversion technologies are considered "energy recovery" and preferable to "treatment and disposal" on EPA's waste management hierarchy. However, the ability to draw life cycle environmental performance conclusions between US conversion technologies to conventional options such as WTE and landfill disposal is limited due to the general lack of conversion technology operational history, experience and available long term data (more than 5 years) to establish environmental and economic performance over time.

In contrast to waste conversion technologies, WTE and landfill facilities have decades of environmental and economic performance data. WTE facilities are required to conduct performance tests and use

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[1] https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy

[2] Michaels and Shiang, 2016. 2016 Directory of Waste-To-Energy Facilities. http://energyrecoverycouncil.org/wp-content/uploads/2016/05/ERC-2016-directory.pdf

[3] Thorneloe, S. 2019. Section 22 "Management of Solid Wastes" (22-69 – 22-93) in *Perry's Chemical Engineers' Handbook*, 9th Edition, New York: McGraw-Hill.

[4] Kaplan PO, DeCarolis J, and Thorneloe S. 2009. Is it better to burn or bury waste for clean electricity generation? Environ. Sci. Technol., 43(6): 1711-1717.

continuous emissions monitoring providing data on 100% of US facilities[5]. Models are used to quantify landfill emissions due to difficulty in measuring fugitive loss from landfills. Landfills are not a steady-state process and are constantly changing due to (1) changes in waste composition, (2) landfill design, operation, and maintenance, (3) barometric pressure and (4) extreme weather events. Once waste is buried, the landfill owner/operator has up to 5 years to install gas collection into the buried waste. As a result, emissions from readily decomposing waste such as food waste is emitted to the atmosphere since there is no capture of the methane (Levis et al., 2010) from waste burial until controls are installed 3 to 5 years after initial burial. Once a landfill "closes" or ceases accepting waste, emissions are thought to decline over time based on the use of a first-order decomposition equation referred to as the landfill gas emissions model (LandGEM)[6]. Satellite data suggest that landfill emissions may be understated by a factor of 2. (Duren et al., 2019) Regardless of the uncertainty in calculating landfill emissions, we have modeled landfills taking into account the uncertainty when comparing emissions to either WTE or waste conversion technologies.

In assessing conversion technologies, it is important to understand which MSW feedstock(s) can be managed by the technology, what pre-sorting or processing is required, whether minimum quantities of MSW must be provided, net energy balance, emissions data, environmental permit requirements, and the types and quantities of solid and hazardous residuals requiring management or disposal.

Technology Landscape

The following table provides an overview of conversion technologies and the potential portion of total US MSW generation that could potentially be managed with these technologies:

Technology	MSW Feedstocks Accepted by Operating Facilities	Portion of Total MSW	Residual Generation Requiring Disposal (by weight)	Number of Facilities Currently Operating in the US
Anaerobic Digestion	Food and yard waste	Approximately 28%	Approximately 5-10%[a]	25+ stand alone multi-source commercial facilities[7]
Gasification	MSW	Approximately 83%[b]	Greater than 10%[c]	2 operating facilities
Pyrolysis	Plastics	Approximately 13%[b]	Greater than 10%	4 operating facilities
WTE	MSW	100%	Approximately 15-25%	73 commercial facilities

WTE, waste-to-energy; MSW, municipal solid waste

[a]does not include digestate which typically is composted

[b]based on the usable fraction of the US average composition of MSW

[c] Gasification will have the same amount of ash potential as WTE but does not convert all the carbon; therefore, it will always have more solid residual than complete combustion as occurs in a WTE facility

[5] Thorneloe, S. 2019. Section 22 "Management of Solid Wastes" (22-69 – 22-93) in *Perry's Chemical Engineers' Handbook*, 9th Edition, New York: McGraw-Hill.

[6] Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide, EPA-600/R-05/047, May 2005.

[7] EPA's Anaerobic Digestion Data Collection Project collects and summarizes data on Anaerobic Digestion Facilities. The 2015 survey results are available at https://www.epa.gov/anaerobic-digestion/anaerobic-digestion-tools-and-resources#ADdata New reports will be published in 2019 and 2020.

This report includes definitions for pyrolysis, gasification and anaerobic digestion (AD) technologies, process descriptions, listings of active projects and facilities in North America, and characterization of life cycle environmental impacts. This report provides an update to the 2012 EPA report, *State of Practice for Emerging Waste Conversion Technologies*, (US EPA, 2012). Key updates include current information about the conversion technology landscape and a literature review to provide data for characterizing the life-cycle environmental performance of technologies. The literature review yielded 60 total studies of which 48 were conducted since 2012.

Through this study, 30 pyrolysis and gasification technology projects and more than 40 operating MSW-based AD facilities were identified in North America. **Figure ES-1** shows the location of stand-alone current active gasification, pyrolysis, and AD projects in North America. While MSW-based conversion technology is still emerging in the US, these technologies have been utilized used for the management of MSW in other parts of the world, such as Australia, Canada, Europe, and Japan albeit in a limited capacity. A key aspect of international applications is that they are part of MSW collection and management systems with advanced material sorting and processing, such as source segregated organics collection.

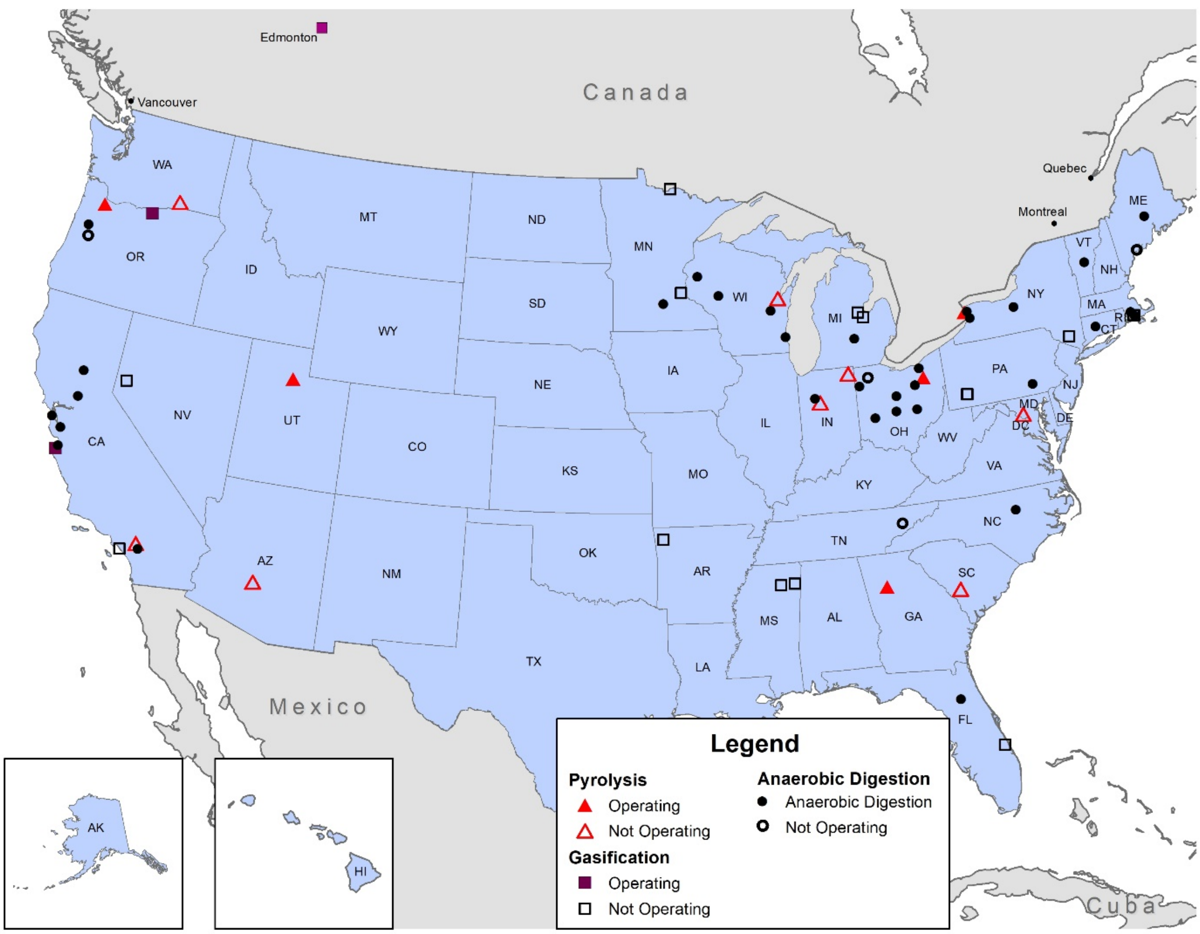

Figure ES- 1. Municipal solid waste conversion facilities.

Since the 2012 EPA report, *State of Practice for Emerging Waste Conversion Technologies* (US EPA, 2012), AD has grown rapidly with more than 25 stand-alone facilities that accept multi-source food waste that process food and other organic fractions of MSW. Additionally, there are many more solely industrial source and wet AD projects diverting food scraps and other organic materials to wastewater treatment plants with excess capacity, but these projects are not included in this report.

Of the 35 gasification and pyrolysis emerging technology companies identified in the 2012 EPA report, six of the companies are operating at commercial or demonstration scale today. Two of the projects, Environ and Green Power Inc., resulted in multi-million-dollar fraud judgements against the CEOs. There are several other projects that have ended with lawsuits and settlements for unpaid services and breaches in contracts. Currently, there are only one gasification and two pyrolysis facilities operating at a commercial scale in the US using fractions of MSW as feedstock.

Siting Facilities

Traditionally, businesses and local agencies involved in the siting of facilities strive to comply with planning and zoning regulations but may overlook the negative physical, social, and economic effects of site activities. Businesses and local agencies that take the time to meaningfully engage communities surrounding proposed facilities and consider the potential burden to vulnerable communities typically have a more efficient permitting process.

In order to better understand communities around conversion technology and conventional WTE facilities, EPA used EJSCREEN to assess income levels around these facilities. EJSCREEN[8] is an online publicly available EPA environmental justice mapping and screening tool that provides a nationally consistent dataset and an approach for combining environmental and demographic indicators.

For this analysis, MSW energy recovery facilities (currently operating and under construction) were mapped and evaluated by state percentile for low-income level within one mile of each facility. **Figure ES-2** compares population and percentile low-income around the facilities. Of the 111 facilities mapped, 29 are surrounded by predominantly low-income communities. Newer technologies tend to be in areas with lower population densities, and older technologies such as mass burn are more often surrounded by denser populations. Therefore, ~25% of the facilities are in low-income communities.

[8] EPA, EJSCREEN: Environmental Justice Screening and Mapping Tool. https://www.epa.gov/ejscreen

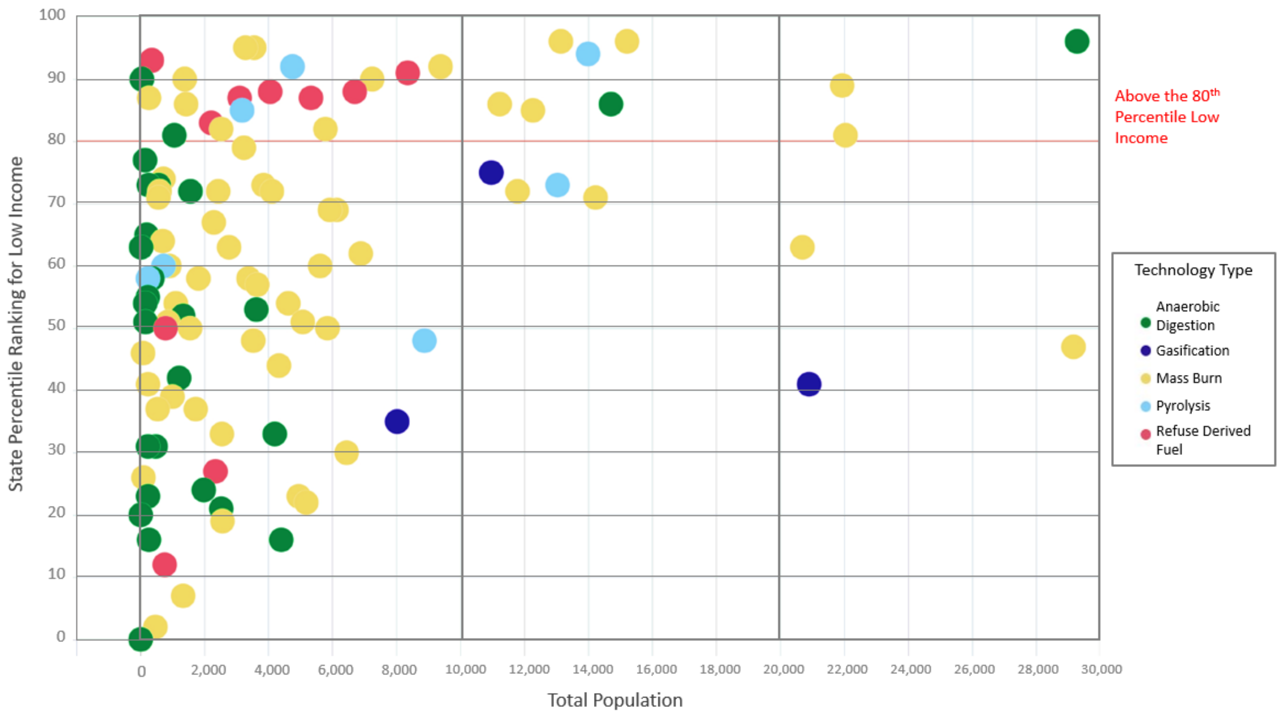

Figure ES- 2. Total population and low-income percentile ranking within one mile of each facility.

Life Cycle Environmental Performance

The ability to draw concrete and definitive conclusions about the life-cycle environmental performance of conversion technologies to each other and to conventional options such as WTE and landfill disposal is limited due to the general lack of operational history, experience and accompanying data. However, from review and analysis of life cycle inventory (LCI) studies available for MSW conversion technologies, the technologies present theoretical energy production benefits comparable to conventional WTE. However, energy production for conversion technologies will vary significantly based on the exact feedstock used, net energy balance, process efficiency and any requirements for preprocessing of feedstock or post-processing of product streams. This is true of any emerging technology especially technologies accepting solid waste, which can also vary by composition and quantity.

Conversion technologies and conventional WTE and landfill options generate gaseous, liquid and solid emissions that require additional treatment or disposal. The literature data summarized in this report suggest that gasification and pyrolysis can result in carbon equivalent emissions comparable to conventional technology.[9] This is due to the carbon emissions associated with the combustion of the

[9]Note that discrepancies can exist between measured data and model estimates for conventional and emerging conversion technologies. Due to the challenges in measuring fugitive loss from landfills, the CAA relies of the use of use of LandGEM – a first-order decomposition equation – that was developed with field data collected in the 1990s (EPA, 2008). Emissions from buried waste occur for decades whereas other technologies produce emissions instantaneously. Landfill measurements are on a on a small-scale basis – not statistically representative. In contrast,

syngas or synfuel product, which is considered fossil energy. Conversely, the use of biogenic (i.e., organic) feedstock in either conventional or conversion technologies will result in a biogenic energy product that is considered carbon neutral. For example, AD of food waste will create biogenic energy that is considered carbon neutral. Likewise, landfills also produce biogenic energy and the organic fraction of waste combusted in a WTE plant (or gasification or pyrolysis) is considered biogenic with respect to carbon accounting.

All conversion technologies produce residual solid, which sometimes include hazardous waste streams (e.g., ash, char, wax, slag, and digestate), that requires additional treatment (e.g., via a compost facility or WTE) or disposal in solid or hazardous waste landfill. Conversion technology by-products may also require treatment or disposal if a viable end-use or market cannot be found. The data available from the literature show that conversion technologies generally produce as much or higher amounts of residuals as conventional WTE. With conventional WTE, approximately five to fifteen percent of the volume[10] remains as ash, which is typically sent to a landfill and often used by the landfill operators as alternate daily cover.

The exact amounts of solid residuals generated will be dictated by the feedstock composition and the level of acceptable contamination by specific conversion technology. In general, it could be expected that a mixed feedstock (e.g., bulk MSW, materials recovery facility [MRF] residuals) will generate greater amounts solid residuals than a source segregated feedstock (e.g., plastics, food waste).

Other challenges found in applying life cycle data to analyze MSW-based conversion technologies include:

- different MSW feedstocks accepted by different technologies and process designs limit the ability to directly compare life cycle results
- wide variety of end-products produced by conversion technologies can create wide-ranging estimates of life cycle offsets
- system boundaries not consistently applied among life cycle studies found in the literature, particularly with regard to the inclusion or exclusion of pre- and post-processing activities
- available life cycle data from the literature represent different time spans and at different points in technology development cycles, which can lead to wide-ranging technology performance estimates

Key Advantages and Challenges

A primary advantage for conversion technologies as compared to WTE or landfill disposal is often presented as the potential variety and flexibility of products that can be generated. Syngas from gasification gas can be used on-site to generate electricity, or it can be further refined to produce a variety

for WTE, data is available for 100% of US facilities which are required to conduct performance tests for multiple pollutants that are compared to health benchmarks. In addition, WTE facilities are required to provide continuous emission monitoring of outlet emissions with data accessible 24/7. For landfills, there are challenges in how best to measure total fugitive loss with leaks occurring in response to drought, soil erosion, and slide slopes. Using ground-based optical remote sensing technology at three landfills, results found fugitive loss ranged from 38 to 88% (US EPA, 2007). Barometric pressure, extreme weather events, and changes in design and operation will result in changes in fugitive loss. Recent data appearing in Nature suggests that current US GHG inventories may be understated for landfill emissions. Therefore, estimates of life-cycle environmental tradeoffs are more uncertain for landfills than for WTE.

[10] https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy

of chemicals, including liquid fuels. Syncrude from pyrolysis can produce high-value products including naphtha, kerosene, and gas-oil, from polyolefin feedstocks. Biogas from AD, or landfill gas, can be used on-site to generate electricity, used directly or it can be further refined to produce transportation fuels. Since there are few operating gasification and pyrolysis facilities in the US, it's not yet clear that they will be able to produce the wide variety of products touted by vendors.

A key challenge for conversion technologies as compared to conventional WTE and landfill disposal is the need for consistent and quality feedstock for the process to work effectively, and in many cases, the limited feedstocks accepted (e.g., plastic, specific plastic resins, organic materials). Unlike WTE and landfill where bulk MSW feedstock is readily accepted, feedstock supply, preprocessing and handling can represent challenges that can have significant impacts on the performance and economics of the conversion technology. Other key disadvantages cited in the literature include difficulties encountered scaling up facilities from demonstration to commercial scale and unpredictable specifications of the energy product that is generated from the conversion technology. These specifications are highly dependent on the types and mixtures of feedstock used.

Another challenge for conversion technologies is the cost, which can include technology and facility costs, permitting, feedstock segregation and processing, operational costs, and disposal or management costs for residuals such as ash or digestate. Put-or-pay contracts, sometimes used by conversion technology companies, obliges the community to either to provide predefined minimum amounts of clean feedstock for a specific period, or to pay for any shortfall. Cost is not only a factor for conversion technologies but also impacts composting, recovery/recycling, and WTE. As shown in Figure ES-3, in 2017 more than 50% (or 140 million tons out of 268 million tons) of MSW generated was buried in landfills in the US (US EPA, 2018). With the current loss in recycling markets, that is also a challenge for communities looking to recover more energy and resources from solid waste.

In addition to the potential financial cost of put-or-pay contract requirements, feedstock quantity shortfalls, the requirements may result in disincentivizing potential and existing waste reduction, reuse, and recycling programs. In Honolulu, a 20-year "put-or-pay" contract requires the City and County of Honolulu's Department of Environmental Services to provide 800,000 tons of MSW annually to the WTE contractor or pay a penalty for any lost revenue from energy sales. From 2013 to 2016, the city had to pay WTE facility contractor over $6.2 million in penalties for not supplying enough waste. Honolulu discontinued public school recycling programs to shift recyclable materials to the WTE facility. Although the "put or pay" contract has a role to play that impacts recycling rates, so does the crash in recyclable commodity values and the lack of markets.[11] Also, the cost to landfill compared to other alternatives including WTE and recycling, results in more waste being landfilled.

Conversion technology facilities are not well established in the US, and an inventory updating the number of facilities in the US that is presented in this report shows a decline in the number of facilities with economics and lack of viable feedstock being a major challenge and resulting in facility closures. For example, of the 35 gasification and pyrolysis facilities identified in the 2012 report, only six are operating in 2019. Some of the companies never got past the planning and funding stage, some couldn't scale up operations, and some resulted in fraud judgements against the conversion technology companies.

In addition to the technical feasibility and performance of waste conversion technologies, there are several key institutional and social challenges that need to be considered including the lack of precedent and ambiguities regarding regulatory permitting and negative public perception. Hence, some stakeholders use the terms "chemical recycling" or "advanced plastic recycling" to describe the use of pyrolysis or gasification to convert plastics.

[11] https://www.civilbeat.org/2017/11/recycle-or-incinerate-the-battle-of-the-blue-bins/

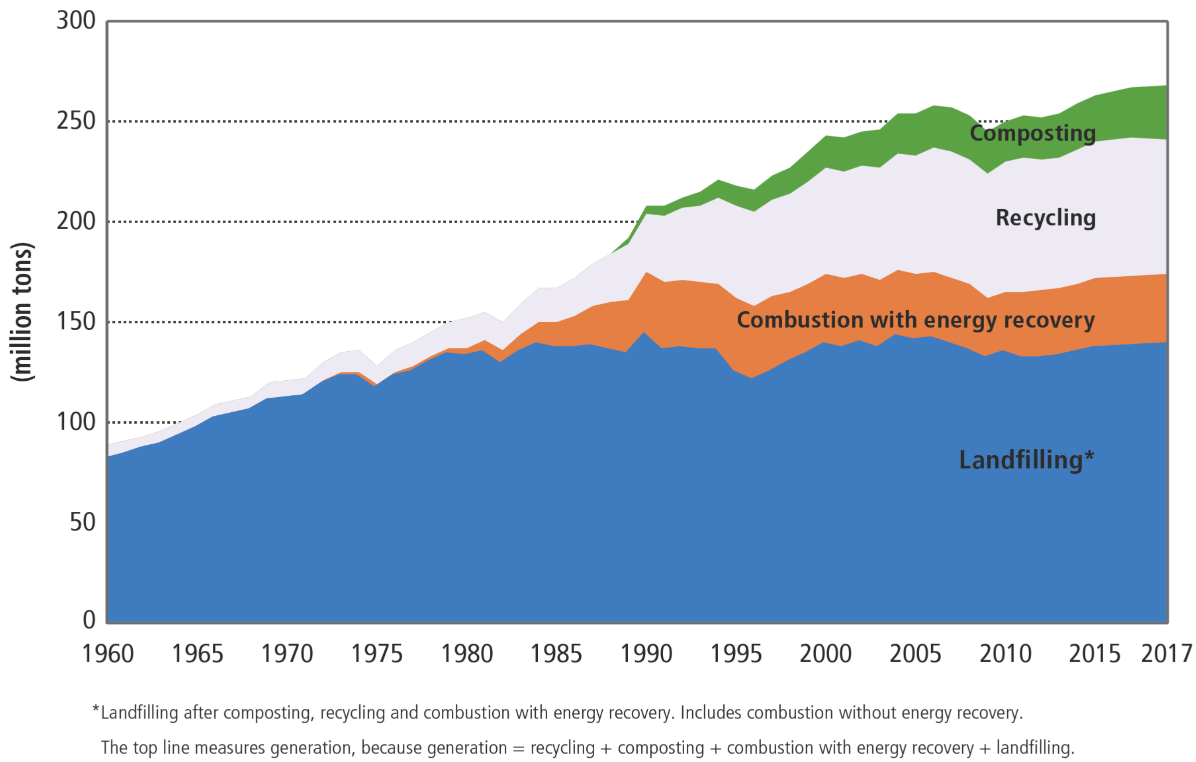

Figure ES- 3. Recycling, composting, combustion with energy recovery and landfilling of materials in MSW, 1960 to 2017.

Key Data Gaps and Recommendations for Future Research

Making direct and meaningful comparisons between conversion technologies and conventional technologies is challenging due to inherent differences among the processes and lack of operating data for characterizing cost and environmental performance.

While operating data may be more readily available in other regions of the world, such as Europe, there is a need for operating data for facilities in the US to better assess their performance with US feedstock and demonstrate their potential in the US context. Therefore, as plants are built, they should be encouraged to submit data relative to cost, energy consumption and environmental concerns.

Additional research that could be done in the future to advance the understanding of conversion technologies might include examining data ranges for operating conversion facilities outside of the US relative to cost and environmental aspects for key parameters such as air, water, and waste emissions; feedstock composition and preprocessing requirements; net energy balance, post-processing requirements for end-products (e.g., syngas cleaning, ash requiring disposal), beneficial offsets for different by-products, and market prices for saleable products.

Additional research on the net energy balance of conversion technologies is also needed. A key consideration for assessing conversion technologies should include an assessment of how efficient the conversion process is. It is not clear whether conversion technology facilities may consume more energy than they produce. In Europe, mechanical biological treatment is in use and should be included in future evaluations. Although the cost is such that there aren't any in the US, if carbon were given a value to increase reductions, then mechanical biological treatment and other technologies may become more advantageous while also protective of human health and the environment.

Research is also needed to collect case studies highlighting permitting challenges and successful solutions on the conversion technologies. This information would be useful to communities evaluating these technologies.

In addition to conducting a review of conversion technologies, a goal of the RESES project is to develop a Decision Makers Guide for Assessing Municipal Solid Waste Energy Recovery Technologies. This is a summary of information contained in the report and is provided as Attachment F. Visuals are provided to illustrate the different options for the different feedstocks in municipal solid waste. For those not wanting the details of the report, they may want to focus on Attachment F.

Executive Summary References

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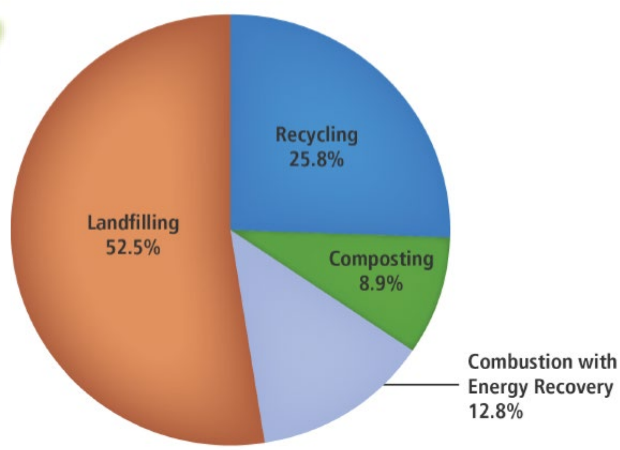
Chapter 1:
Introduction

Sustainable Materials Management is a systemic approach to using and reusing materials more productively over their entire life cycles. It represents a change in how society thinks about the use of natural resources and environmental protection. By looking at a product's entire life cycle, we can find new opportunities to reduce environmental impacts, conserve resources and reduce costs.

The US Environmental Protection Agency (EPA) developed the non-hazardous materials and waste management hierarchy in recognition that no single waste management approach is suitable for managing all materials and waste streams in all circumstances. The hierarchy ranks the various management strategies from most to least environmentally preferred. The hierarchy places emphasis on reducing, reusing, and recycling as key to sustainable materials management. Source reduction can result from any activity that reduces the amount of a material or agricultural input needed and therefore used to make products or food. It is important to recognize that source reduction, reuse, recycling, and composting have been identified as preferred materials management approaches preferred over energy recovery. Discards to landfills is the least preferred and results in emissions over multiple decades as biodegradable waste decomposes.



1.1 Current State of Energy Recovery From Municipal Solid Waste in the US

Recovering energy from waste has long been an attractive concept. Waste needs to be managed and there is a seemingly endless supply, so much so that it's considered a renewable fuel. In 2017, Americans generated approximately 268 million tons of municipal solid waste (MSW), which is the trash thrown away by consumers.[12] More than half of it was landfilled and a quarter was recycled. Nearly 13% (33.6 million tons) was combusted with energy recovery at waste-to-energy (WTE) facilities. The US Energy

[12] US EPA. "Advancing Sustainable Materials Management: 2017 Factsheet." November 2019. EPA530-F-19-007.

Information Administration reported that in 2015, WTE facilities provided about 0.4% of the total US electricity generation and had a total generating capacity of 2.3 gigawatts[13].

Currently, there are 73 WTE facilities operating in the US, with the majority utilizing mass burn combustion (Appendix A). Most of these facilities have been operating for more than 20 years. The West Palm Beach WTE facility started operation on July 18, 2015 and was the first one built since 1995.[14] More recently, the focus has been on emerging waste-to-energy technologies that convert waste into energy products rather than burn it in a combustion unit. These "conversion technologies" differ from mass burn WTE facilities in that they do not directly combust feedstock but rather convert it via partial-oxygen or oxygen-absent thermochemical processes. The resulting gases can be combusted to produce electricity or further processed into a liquid fuel or chemical commodity product. Another difference that makes it difficult to compare emerging technologies to demonstrated technologies is the lack of longer-term data (greater than 5 years) to establish economic and environmental performance. Often, only vendor data is available, which tend to provide optimistic claims.

For the purposes of this report, conversion technologies of focus include gasification, pyrolysis, and anaerobic digestion (AD). The heterogenous nature of MSW makes it challenging to efficiently create energy products from a feedstock that has a widely varying chemical constituency.[15] To address this, the MSW feedstock needs to be effectively sorted or separated and processed. None of the conversion technologies can convert MSW to an energy product without sorting and processing. Furthermore, no country to date has had favorable experience using MSW as feedstock for gasification or pyrolysis. However, there is wider use in other countries – as in the US - of anaerobic decomposition for food waste that prevents landfilling of food waste and permits recovery of nutrients for healthy soil.

1.2 Report Objectives and Structure

As these conversion technologies are being promoted and distributed by private sector stakeholders across the US, local communities and municipalities will need to better understand not only the novelty and potential of each technology type, but also the potential technical, environmental, economic and social impacts of the technologies in their local context. Because of the high-cost failure of numerous conversion technology projects, the National Waste and Recycling Association and the Solid Waste Association of North America developed a "Briefing for Elected Officials" including an "Emerging Waste Management Technology Project Development Checklist."[16]

This report aims to be a resource for communities wanting to better understand these technologies, their risk profiles, and how their life-cycle environmental impacts compare to conventional options for energy recovery from MSW. Chapter 2 provides an overview of conventional options for energy recovery from MSW including landfill and WTE systems. Chapters 3—5 include definitions, process descriptions and existing facilities for emerging gasification, pyrolysis and AD. Chapter 6 includes life cycle inventory

[13] https://www.eia.gov/todayinenergy/detail.php?id=25732
[14] MSW Management. James Warner. *Waste-to-Energy: The Lost Decades.* July/August 2015.
* Select facilities in Canada are also included as they provide direct operational experience.
[15] Joint Institute for Strategic Energy Analysis, "Waste Not, Want Not: Analyzing the Economic and Environmental Viability of Waste-to-Energy (WTE) Technology for Site-Specific Optimization of Renewable Energy Options." February 2013. https://www.nrel.gov/docs/fy13osti/52829.pdf
[16] National Waste and Recycling Association of North America and Solid Waste Association of North America, Briefing for Elected Officials Effective Responses to Emerging Waste Management Technology Proposals (February 2017), and Emerging Waste Management Technology Project Development Checklist (February 2017) https://cdn.ymaws.com/wasterecycling.site-ym.com/resource/resmgr/docs/Unsolicited-proposals-and-em.pdf and https://cdn.ymaws.com/wasterecycling.site-ym.com/resource/resmgr/docs/Emerging-technologies-projec.pdf

(LCI) data available from the literature for emerging technologies and life-cycle environmental comparisons of those technologies to conventional options. EPA's municipal solid waste decision support tool (MSW DST[17]) was used to develop the LCI profiles for conventional options. Chapter 7 provides a summary of findings and observations including key data gaps and recommended future research needs. Attachment C provides a list of additional definitions.

1.3 Quality Assurance and Data Limitations

This project involved collecting and analyzing secondary data for technologies to recover energy from MSW. The data and information contained in this report were collected from the publicly available literature for emerging energy recovery technologies in combination with modeled data developed by applying EPA's MSW DST using US national average assumptions.

This work was conducted under an approved quality assurance project plan. The appropriateness of the data and their intended use were assessed with respect to the data source, the data collection timeframe, and the scale of the geographic area that the data represent. Preference was given to data that have undergone peer or public review (e.g., those published in government reports and peer-reviewed journals) over data sources that typically do not receive a review (e.g., conference proceedings, trade journal articles, personal estimates). However, where peer-reviewed data did not exist, parameters and assumptions were developed from the next highest quality available sources (e.g., grey literature, and product specification data sheets from manufacturers). Preference was given to more recent data over older data. In this report, the sources of all data and any identified assumptions and limitations are presented.

[17] https://mswdst.rti.org/

Chapter 2: Conventional Energy Recovery from Waste

Landfill and direct combustion have been traditional management options for MSW in the US. There are almost 600 operational landfill gas to energy projects in the US, most of which utilize landfill gas to produce electrical energy.[18] Today's MSW combustion plants operating in the US are designed to generate electricity (and possibly heat) and recover recyclable metals. Because these plants combust MSW and recover energy, they are often called waste-to-energy (WTE) plants or resource recovery facilities. Common technologies for the combustion of MSW include mass burn facilities, modular systems and refuse-derived fuel systems. According to the US Energy Information Administration, in 2016, 71 WTE (mass burn and refuse-derived fuel (RDF) plants generated approximately 14 billion kilowatt hours of electricity from burning 30 million tons of MSW, comprised primarily of biomass and plastics.[19]

Although the focus of this report is evaluating waste conversion technologies, landfills and combustion are included to provide a basis for comparison. The ideal goal is to maximize resource and energy recovery from waste and minimize the impact of waste management on human health and the environment. Energy can be recovered from landfills but not as efficiently as combustion of waste. Kaplan et al. (2009) found that WTE (or mass burn combustion) can generate an order of magnitude more electricity than landfill gas to energy given the same amount of waste. Only the biodegradable portion of landfilled waste contributes methane and the inefficiencies in gas collection and capture result in much of the methane leaking and not being utilized for its energy potential. Whereas, mass burn or waste conversion does recover more resources and generate more electricity as compared to landfilling.

2.1 Landfill

In the US, more than 140 million tons (or 52%) of MSW is landfilled (US EPA, 2019). Biodegradable components such as food waste, paper, yard debris, septic sewage sludge and other organics will decompose and produce methane that can be captured and utilized for its energy value. Figures 1 and 2 provide a distribution landfill gas to energy projects using data provided by EPA's Landfill Methane Outreach Program (LMOP).

In the US, municipal landfills are required to meet federal Resource Conservation and Recovery Act (RCRA) Subtitle D design and operation standards, codified in 40 CFR 258, which require that the facility, among other requirements, have a composite liner system, final cover, and groundwater monitoring system. Landfills are also required to meet federal Clean Air Act standards that require collection and capture of gas prior to combustion in a flare or to generate electricity using gas-fed or steam-fed turbines, lean-burn or rich burn engines, or to replace boiler fuel with landfill gas. The landfill air rules[20] require that gas be collected within 3 to 5 years of waste burial. As a result, gas generated over this time is emitted to the atmosphere (Levis et al., 2010). Even once gas is collected, the capture efficiency has been found to range from 38 to 88%[21] meaning that not all methane is captured and

[18] https://www.epa.gov/lmop/landfill-gas-energy-project-data

[19] US Energy Information Administration. Waste-to-energy. https://www.eia.gov/energyexplained/?page=biomass_waste_to_energy

[20] https://www.epa.gov/stationary-sources-air-pollution/municipal-solid-waste-landfills-new-source-performance-standards

[21] Quantifying Methane Abatement Efficiency at Three Municipal Solid Waste Landfills, EPA/600/R-11/033, Jan 2012.

controlled. Methane is a potent greenhouse gas 28 to 36 times more effective than CO_2 at trapping heat in the atmosphere over a 100-year period.[22]

With the cost of landfills less than other management options and without a value for environmental externalities such as carbon emissions, most communities will continue to discard residential and commercial waste in a landfill. However, recent reports suggest that landfill carbon emissions may be understated as compared to oil and gas industry and the agriculture industry (Ren et al., 2018; Peischl et al., 2013). Through testing using satellites by the National Oceanic and Atmospheric Administration (NOAA), the largest methane emitters in California were found to be 30 landfills contributing 41% of total methane emissions (Duren et al., 2019). Using landfill gas to generate energy and reduce methane emissions produces positive outcomes for local communities and the environment. Landfill gas utilization projects reduce carbon emissions, reduce air pollution by offsetting the use of non-renewable resources, reduce environmental compliance costs, provide health and safety benefits, and can provide benefit to the community and economy. As shown in Figure 1, there are almost 600 operating projects with the majority producing electricity (Figure 2).

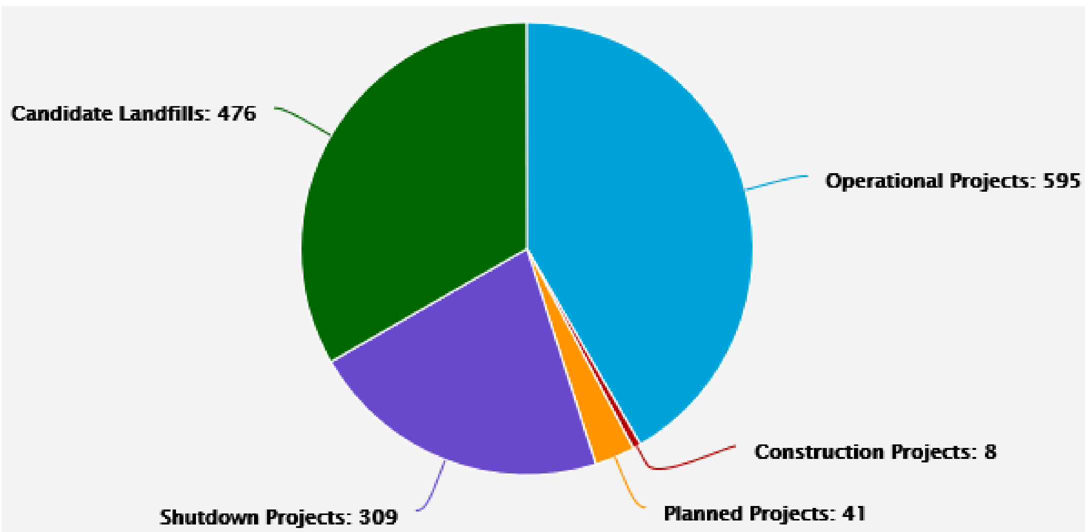


Figure 1. Landfill gas to energy project in the US (2019).

22 https://www.ipcc.ch/report/ar5/syr/

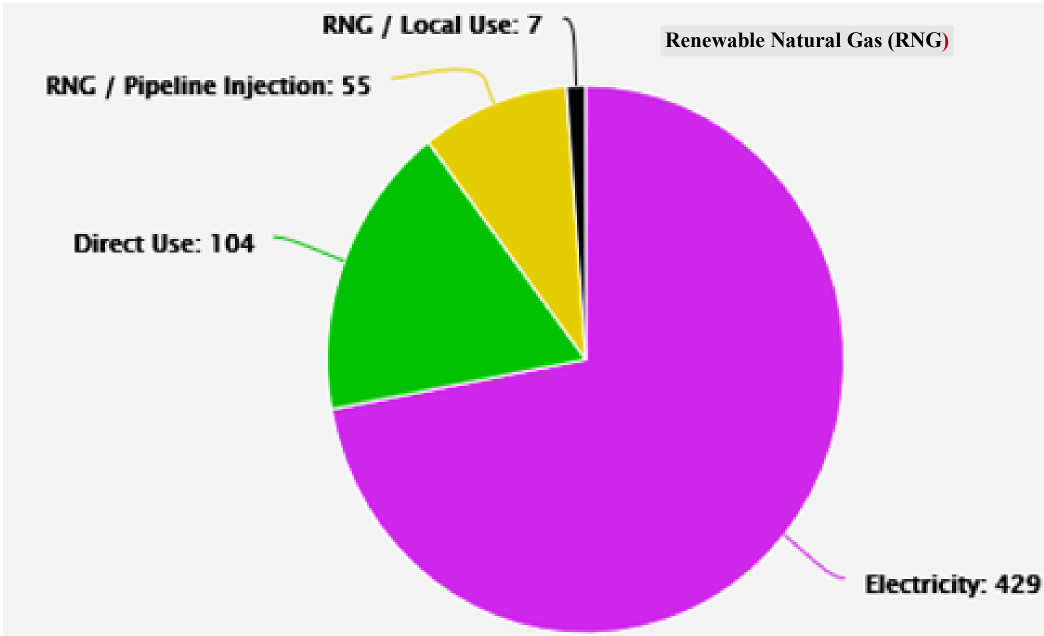


Figure 2. Operational landfill gas to energy projects by type in the US (2019). [23]

Figure 3 presents a process flow diagram for a conventional MSW landfill. As shown, incoming waste is deposited on the working face of the landfill where it is spread, compacted, and covered with daily cover material (usually soil). Once the active cell is filled, intermediate cover will be placed on the cell and a new cell opened. When all cells at the site have been filled, a final cover system will be installed although often interim caps are used prior to a final cover installation.

[23] https://www.epa.gov/lmop/basic-information-about-landfill-gas#landfill

Figure 3. Process flow diagram for a conventional MSW landfill.[24]

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[24] Source: https://www.tes.com/lessons/gfhTlsasHKQqeg/why-should-we-care-about-garbage

The quantity and composition of the MSW in the landfill directly impacts landfill gas production. A landfill that accepts large fractions of organic wastes, for example, will generally have higher greenhouse gas (GHG) emissions than a landfill that accepts little organic wastes or only inorganic materials. The composition of landfill gas is generally assumed to be 50% CH_4 and 50% carbon dioxide (CO_2) based on volume (US EPA, 2011). The CO_2 fraction of landfill gas is considered biogenic in nature and has an associated global warming potential (GWP) of zero. CO_2 emissions that are produced from landfill gas combustion using a flaring or energy recovery system are also considered biogenic. Combustion of landfill gas via a flare and/or energy recovery system will destroy almost all of the CH_4, converting it to CO_2. However, landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen; less than 1% non-methane organic compounds (NMOCs); and trace amounts of inorganic compounds (US EPA, 2014b). Where landfill gas is combusted in a flare and/or energy recovery system, criteria and hazardous air pollutants are generated (US EPA, 2008 and 2007).

Landfill gas can escape the gas collection system and pass through the cover soil, cracks in the cover or leaks around the gas wells. For landfill gas that passes through the cover soil, a fraction of the CH_4 can be oxidized by methanotrophic organisms in the soil. The exact fraction of CH_4 oxidized will vary by site-specific conditions. Landfill gas takes the path of least resistance and leaks occur that will vary over time based on changes in landfill design and operation. As stated earlier, landfill owner/operators have up to 3 to 5 years to install gas control, meaning all gas being generated during that time is lost to the atmosphere. Also, landfills operate for decades and once they cease accepting waste, there can be emissions for many decades in the future. The Subtitle D requirements, codified in 40 CFR 258, require liners and leachate control system be used to limit waterborne contaminants in the uppermost aquifer within prescribed limits. In states that have received EPA program approval for 40 CFR 258.4 research, development, and demonstration permits, MSW landfills can also be managed as “wet” landfills where liquids are added to enhance biodegradation of organics and gas production for energy recovery. The amount of leachate generated is generally governed by the moisture content of the MSW and the precipitation at the landfill. Post-placement of MSW, the fraction of precipitation that becomes leachate will decrease as the buried waste is covered with an intermediate and/or final cover. Leachate collection systems are designed to capture the leachate so that it can be removed from the landfill and treated on- or off-site. Thus, the releases for waterborne contaminants from the landfill include the post-treatment releases as well as any releases that escape the leachate collection system. (Thorneloe, 2019)

2.2 Mass Burn Facilities

The majority of WTE plants in the US use mass burn combustion to burn waste to generate heat and electricity. Attachment A lists the 63 currently active mass burn plants in the US. Attachment A also list 13 refuse-derived fuel (RDF) and 4 modular (i.e., portable) WTE plants. Most of these facilities have been operating for more than 20 years. Only one new WTE facility has been built since 1995.[25] As shown in **Figure 4**, a mass burn WTE plant accepts unprocessed MSW, which is burned in a large combustion unit with a boiler. Steam from the boiler is used to generate electricity or utilized in a combined heat and power system. Ferrous metal and other metals are recovered and recycled.

[25] James Warner. *Waste-to-Energy: The Lost Decades.* MSW Management. July/August 2015.
* Select facilities in Canada are also included as they provide direct operational experience.

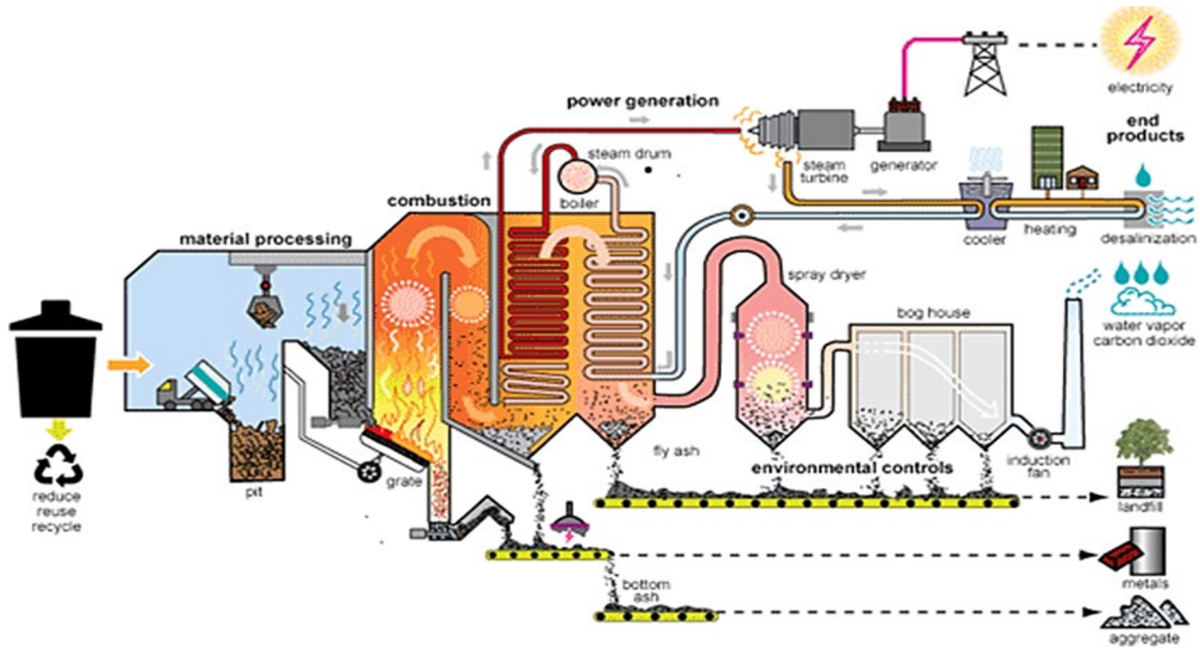


Figure 4. Mass burn process flow diagram (US EIA, 2018).

(Note: Fly ash and bottom ash are shown as being treated separately, which is common in Europe. In the US, the ashes are typically handled together as a combined ash)

An air pollution control system cleans the combustion gases, to levels significantly below Maximum Achievable Control Technology (MACT) regulatory standards, prior to their release to the atmosphere. The amount of combustion residues, or ash, generated depends on the composition of the MSW combusted and ranges from 15-25 percent (by weight) and from 5-15 percent (by volume) of the MSW processed.[26] Generally, MSW combustion residues consist of two types of material: fly ash and bottom ash. Fly ash includes fine particles removed from the flue gas and residues from other air pollution control devices, such as scrubbers. Fly ash typically amounts to 3-7% percent by weight of the total ash. Bottom ash comprised the remaining ash by weight and includes the main chemical constituents such as silica (sand and quartz), calcium, iron oxide, and aluminum oxide as well as un-oxidized amounts of iron and aluminum. In the US, the bottom and fly ash streams are mixed together at the facility and handled as a combined ash. Combined bottom ash usually has a moisture content of 20-30 percent by dry weight. The chemical composition of the ash varies depending on the original MSW feedstock and the combustion process. The ash that remains from the MSW combustion process is typically sent to landfills, either as beneficial daily cover, co-mingled with regular MSW, or in a separate ash monofill.

2.3 Modular Systems

Modular WTE Systems burn unprocessed MSW. They differ from mass burn facilities in that they are much smaller and are portable. They can be moved from site to site. Attachment A list 4 modular WTE plants.

[26] https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw#HowWorks

2.4 Refuse-Derived Fuel Systems

Refuse-derived fuel systems use mechanical methods to shred incoming MSW, separate out non-combustible materials, and produce a combustible mixture that is suitable as a fuel in a dedicated furnace or as a supplemental fuel in a conventional WTE boiler system. After shredding and noncombustible materials are removed, the remaining material is either conveyed to a nearby RDF combustion facility for use or transported to an RDF combustion facility (or possibly to an industrial or utility user) located elsewhere. The RDF can either be used as-is (shredded fluff) or compressed into pellets, bricks, or logs for transportation, storage or sale. RDF processing facilities are typically located near a source of MSW, while the RDF combustion facility can be located elsewhere. RDF is often combusted with other biomass materials or with fossil fuels to produce renewable energy sources.

According to the Energy Recovery Council (Michaels and Shiang, 2016), there are 13 RDF WTE plants operating in the US. **Table 1** provides a listing of facilities that make RDF from MSW or combust RDF.

2.5 Non-Waste Fuel NHSM Combustion for Energy

Another type of refuse-derived fuel WTE system being built today aims to make an engineered non-waste fuel out of MSW, or other non-hazardous waste materials, for off-site use in a cement kiln or boiler to supplement or as a substitute for traditional fuels. This type of RDF requires more sorting and processing than traditional RDF and typically aims for a high-BTU/lb fuel with low moisture and low chloride content. Additionally, this engineered non-waste fuel requires a site-specific non-waste fuels determination following the requirements of the Resource Conservation and Recovery Act (RCRA) Non-Hazardous Secondary Material (NHSM) rule.

The NHSM rule identifies criteria for determining which NHSMs are, or are not, solid wastes when used as fuels or ingredients in combustion units. Units combusting NHSMs that are solid waste are subject to the requirements of Section 129 of the Clean Air Act (CAA), while units that combust NHSMs that are not solid waste may be subject to regulations promulgated under CAA Section 112. The NHSM rule was developed under the RCRA in conjunction with three rules under the Clean Air Act-the major boiler, area boiler and the commercial and industrial solid waste incineration rules. The rules are codified at 40 CFR Parts 60 and 241.

Under CAA Section 129 EPA has issued emission standards for Commercial and Solid waste Incinerators (the CISWI rule). The types of facilities under the CISWI rule are boilers and process heaters, industrial furnace and incinerators. Under section 129 of the Act, the standards include limiting emissions of nine air pollutants (i.e., particulate matter, carbon monoxide, dioxins/furans, sulfur dioxide, nitrogen oxides, hydrogen chloride, lead, mercury, and cadmium). Section 129 standards apply to any facility that combusts any commercial or industrial solid waste material, including those that combust solid waste for energy recovery purposes.

NHSMs that are combusted are generally considered solid waste. If a unit does not combust a material that the NHSM rule defines as a solid waste, the unit will instead be subject to the 112 NESHAP standards. NHSMs that are considered non-wastes when combusted are identified in 40 CFR 241.3 and 241.4 and can be subject to emissions standards under CAA section 112 for control of Hazardous Air Pollutants from sources such as utilities, boilers, process heaters and cement kilns.

There are three routes to a non-waste NHSM determination that determine whether a material is a waste or a non-waste:

1. **Site-specific "self-determination" requirements under 40 CFR 241.3(b).** A combustion source must make a waste or non-waste determination for the NHSM used as fuel managed within their control (241.3(b)(1)); or for ingredients (241.3(b)(3)); or for fuel or ingredient products produced from processed discarded NHSM (241.3(b)(4)).

2. **Petitions under 40 CFR 241.3(c).** Sources may petition for a non-waste determination from the EPA Regional Administrator for a material used as a fuel that has not been discarded and is not managed within their control.

Table 1. Facilities that make RDF from MSW or Combust RDF in the US

Operational Status	Facility Name & Operator	City	State
Operating - makes RDF from MSW	Prairieland Solid Waste Management Resource Recovery Facility	Truman	MN
Operating - makes RDF from MSW	Recycling & Energy Center Ramsey/Washington Recycling and Energy Board	Newport	MN
Operating – combusts RDF	Mid-Connecticut Resource Recovery Facility NAES Corp.	Harford	CT
Operating – combusts RDF	Miami-Dade County Resource Recovery Facility Covanta Dade Renewable Energy, LLC	Miami	FL
Operating – combusts RDF	Palm Beach Renewable Energy Facility #1 Babcock & Wilcox	West Palm Beach	FL
Operating (this facility also utilizes mass burn) – combusts RDF	Honolulu Resource Recovery Venture-HPOWER Covanta Honolulu Resource Recovery Venture	Kapolei	HI
Operating– combusts RDF	Arnold O. Chantland Resource Recovery Plant City of Ames	Ames	IA
Operating– combusts RDF	Penobscot Energy Recovery Company ESOCO Orrington, Inc.	Orrington	ME
Operating– combusts RDF	SEMASS Resource Recovery Facility Covanta SEMASS, L.P.	West Wareham	MA
Operating – combusts RDF	Detroit Renewable Power Detroit Renewable Energy, LLC	Detroit	MI
Operating – combusts RDF	Red Wing Steam Plant Northern States Power Co - Minnesota	Red Wing	MN
Operating – combusts RDF	Wilmarth Plant Northern States Power Co - Minnesota	Mankato	MN
Operating – combusts RDF	Wheelabrator Portsmouth Wheelabrator Portsmouth Inc.	Portsmouth	VA
Operating– combusts RDF (mostly biomass/wood)	French Island Generating Station Northern States Power Co - Minnesota	La Crosse	WI
Closed 2019[27]	Elk River Station Great River Energy	Maple Grove	MN

MSW, municipal solid waste; RFD, refuse-derived fuel

[27] EE Online. *Great River Energy: Elk River project stops operations, prepares for closure.* Feb. 25, 2019. https://electricenergyonline.com/article/energy/category/biofuel/83/750958/elk-river-project-stops-operations-prepares-for-closure.html

3. Categorical non-waste determinations under 40 CFR 241.4. Materials that are listed in 40 CFR 241.4(a) have been determined to be non-waste materials by the EPA Administrator, so do not need to conduct a site-specific determination for these materials. A source may petition the Administrator for a categorical non-waste determination under 40 CFR 241.4(b).

Under the NHSM Rule, the determination that a waste material has been processed into a non-waste fuel is made by the facility and is self-implementing. Specifically, the NHSM Rule regulations require that a facility processing waste material into a fuel perform a demonstration showing that the material and site-specific process satisfy 40 CFR 241's processing and legitimacy requirements and maintain such demonstration in their records and provide such demonstration to facilities who would combust the non-waste fuel.

Although not required, some facilities have sought EPA concurrence on their determinations and, in some instances, EPA has issued clarification letters for projects that have processed MSW waste material into an engineered fuel product. EPA's letters[28] concurred, for those instances, that the facilities had provided an adequate demonstration showing their materials were processed into a new fuel product (per 40 CFR 241.3(b)(4)), meeting the processing definition of 40 CFR 242.2 and the legitimacy criteria 40 CFR 241.3(d)(1). Copies of these EPA concurrence letters are available at: https://rcrapublic.epa.gov/rcraonline/topics.xhtml#W

Table 2 provides a listing of facilities that are or are planning to process MSW into a non-waste fuel and have made a site-specific "self-determination" satisfying the requirements of 40 CFR 241.3(b). This list was pulled from RCRA Online of organizations that have received NHSM clarification letters from EPA[29].

Table 2. Facilities that Process MSW into a Non-Waste Fuel for Combustion in the US

Operational Status	RCRA Online Number	Facility Name & Operator	City	State
Under construction[30] – will make solid recovered fuel from MSW	14863	Accordant Energy LLC (formerly ReCommunity) / RePower South LLC	Moncks Corner	SC
Under construction – will make solid recovered fuel from MSW	14838	Entsorga West Virginia	Martinsburg	WV
Both facilities recently closed[31] - makes solid recovered fuel from MSW	14869	Waste Management SpecFUEL	San Antonio Philadelphia	TX PA
Expected to be operational in 2019[32] – will make solid recovered fuel from MSW	14909 14910	Coastal Resources of Maine / Fiberight LLC[33]	Hampden	ME

MSW, municipal solid waste; RCRA, Resource Conservation and Recovery Act

[28] https://rcrapublic.epa.gov/rcraonline/topics.xhtml#W
[29] EPA Clarification Letters are available on RCRA Online at https://rcrapublic.epa.gov/rcraonline/topics.xhtml#W
[30] Biomass Magazine. Accordant Energy LLC. *Construction begins on facility producing MSW-derived fuel.* March 8, 2018. http://biomassmagazine.com/articles/15127/construction-begins-on-facility-producing-msw-derived-fuel
[31] As of Sept 2020, Waste Management confirmed that both sites are closed.
[32] Mainebiz. *Fiberight $70M waste-to-energy plant finally ramping up.* 20 Feb 2019.
[33] Fiberight facility was just sold; do not know if operations will continue

Chapter 3: MSW Gasification

Gasification is a thermal process that, in a controlled oxygen environment, converts organic or fossil fuel carbon-containing material – such as coal, petroleum, plastics, or biomass – to syngas, char, and ash. The process is similar to pyrolysis, except that oxygen (as air, concentrated oxygen, or steam) is added to maintain a reducing atmosphere in the reactor. A reducing atmosphere exists when the quantity of oxygen available is less than the stoichiometric ratio for complete combustion. The process primarily forms carbon monoxide and hydrogen, and other constituents such as methane, particularly when operating at lower temperatures. The primary product of gasification, syngas, can be converted into heat, power, fuels, fertilizers and chemical products, or used in fuel cells.

3.1 MSW Gasification Process Description

The literature and technology vendors use different names for gasification and different variations for gasification processes in their technology descriptions which can cause confusion. Technological processes can be simplified into three core types of gasification, including:

- **High temperature gasification**—High temperature gasification reactors can reach up to 1,200 °C and produce an inert byproduct, or slag, that does not need further processing to be stabilized. The syngas produced may be combusted to generate steam, which can be used for power and/or heat generation; however, the resultant syngas may also be used for other applications such as chemicals production. This technology may process a mix of carbonaceous waste including paper, plastics, and other organics with a moisture content of up to 30%. Higher moisture content feedstock would likely require drying before entering the reactor chamber.
- **Low temperature gasification**—Low temperature gasification reactors operate at temperatures between 600 and 875 °C and produces syngas as the main product and ash as a byproduct, which may require stabilization. The ash can be sent to a vitrification[34] process to makes it inert and available for other uses. Syngas is typically used for electricity generation using an Internal Combustion Engine. This process can also recover steam energy.
- **Plasma gasification**—Plasma gasification converts the selected waste streams which can include paper, plastics, organics, biomedical waste hazardous waste and hazmat materials to syngas and slag. In this technology, the gasification reactor uses a plasma torch where a high-voltage current is passed between two electrodes to create a high-intensity arc, which in turn rips electrons from the air and converts the gas into plasma or a field of intense and radiant energy with temperatures more than 1000 °C. The heated and ionized plasma gas is used to treat the feedstock and produce syngas and slag.

3.1.1 General Process Flow

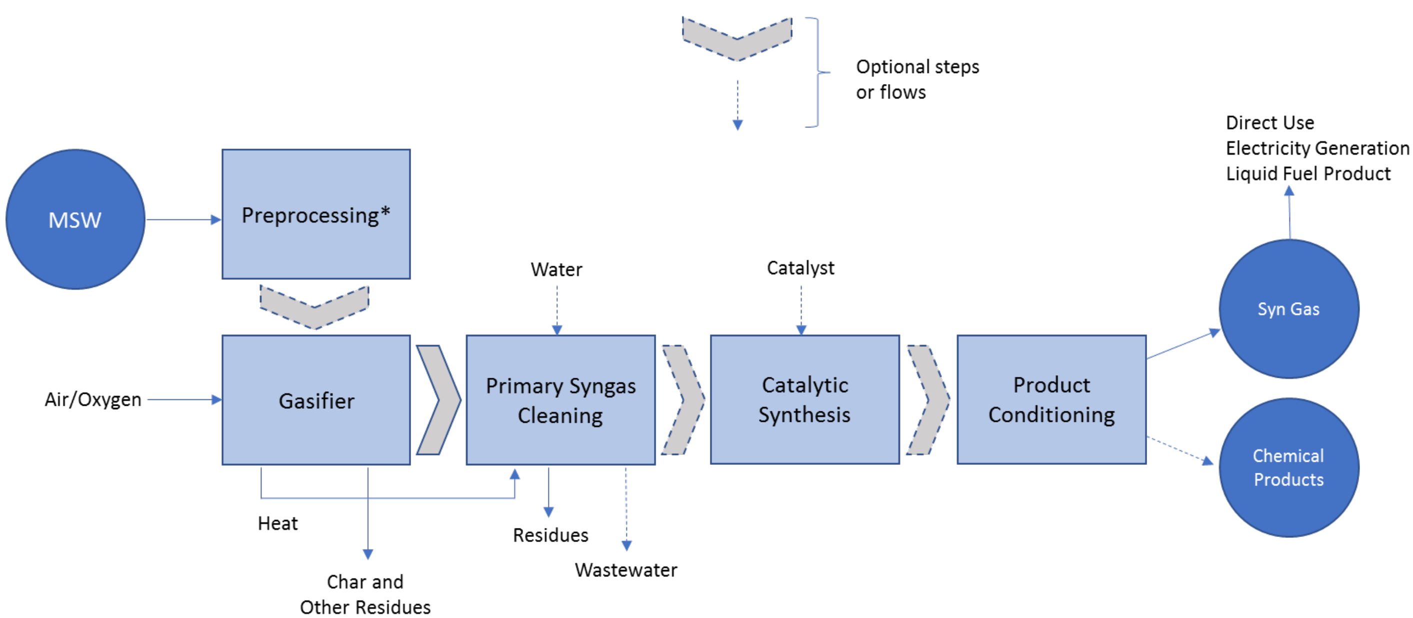
Despite variations in operating cost, efficiency and processing capacity among the technologies profiled in this report, most gasification technologies follow a general process flow which is illustrated in **Figure 5** and outlined below.

1. **MSW Feedstock:** MSW feedstock accepted at gasification facilities will typically require additional processing regardless. Depending on the specific composition of the MSW feedstock

[34] Vitrification is a waste disposal method to immobilize and encapsulate materials. In the vitrification process, high temperatures (1100ºC-1600ºC) are employed to melt the materials into a liquid which on cooling, transforms the material into an amorphous glass like solid and permanently captures the waste.

received, preprocessing may be required, or the feedstock may be used as-is for immediate input into the gasifier.

2. **Preprocessing:** In most cases, preprocessing of the MSW feedstock is used to remove any unwanted materials. In addition, shredding of the feedstock is typical to create more homogenous-sized particles prior to input to the gasifier.
3. **Gasifier:** Feedstock is fed into the gasifier along with a controlled amount of air or oxygen (and possibly steam). A sequence of reactions takes place, with temperatures ranging from 593 to 892 °C, and syngas is produced. Solid residues (e.g., char) also are produced and removed from the gasifier and sent to disposal (or possibly reused).
4. **Primary Syngas Cleaning:** Initial syngas cleaning is designed to remove impurities (e.g., dust, ash, tar) so that the gas can be used in combustion engines.
5. **Catalytic Reaction / Purification:** Further purification of syngas includes removal of carbon monoxide and impurities, such as heavy hydrocarbons, hydrogen sulfide, ammonia, hydrogen chloride, methane and other trace contaminants by a catalytic synthesis. While the catalysts used by profiled companies are proprietary, biogas plants conventionally will use transition metals, reforming catalysts like ruthenium (Ru), palladium (Pd), platinum (Pt), rhodium (Rh) and nickel (Ni) based catalysts for catalytic reactions / purification.
6. **Product Conditioning:** Depending on the specific fuel characteristics or chemical product requirements, additional conditioning may be required.



*Preprocessing can include shredding, screening, washing and/or drying depending on MSW feedstock.

Figure 5. General MSW gasification process flow diagram.

3.1.2 Process Flow Variations

Several variations exist in gasification process design that present individual challenges and opportunities for operators. In this section, the most common challenges and considerations in gasification applications as found in the literature are summarized.

Common Gasification Process Designs

- **Integrated Gasification Combined Cycle (IGCC).** IGCC plants feed a carbon resource into the gasifier with oxygen and steam that respectively produces raw syngas. The raw syngas is cleaned of particulate matter and sulfur and subsequently fed into a combustion turbine (e.g., for heat recovery and power generation). A key variation in IGCC plants relates to whether carbon is captured (e.g., through reactions with water) as IGCC plants typically do not require CO_2 separation.
- **Fixed/Moving Bed Gasification.** Non-slagging and slagging versions of fixed/moving bed gasification, both process feedstock in a counter current flow of gas and solids. A key challenge of this gasification process relates to the inconsistency and agglomeration of particles that hinder inter-phase mixing, reacted carbon and conversion rates. This simpler process of fixed/moving bed gasification, where gas and solids move in a co-current manner is similar to many other gasification process types including entrained flow gasification. (In entrained-flow gasifiers, fine coal feed and the oxidant [air or oxygen] and/or steam are fed co-currently to the gasifier. This results in the oxidant and steam surrounding or entraining the coal particles as they flow through the gasifier in a dense cloud. Entrained-flow gasifiers operate at high temperature and pressure—and extremely turbulent flow—which causes rapid feed conversion and allows high throughput.)
- **Fluidized Bed Gasification.** Fluidized bed gasification allows for a well-mixed reaction where processes take place simultaneously throughout bed. While more complicated to operate, this gasification process allows for more optimal mixing of gas and solids, lower ash rates on particles and better conversation rates.

Common Variations in Gasification Process Designs

- **Atmospheric vs. Pressurized.** Gasifiers can operate at both atmospheric or pressurized levels (as high as 900 psia). Atmospheric and pressurized levels contribute to the gasification process in various ways. A highly pressurized gasifier for example, complements an IGCC operation through feeding syngas directly into the fuel control system of the gasifier. Higher pressure gasification mitigates the cost and difficulty of cleanup operations, due to producing a less voluminous flow of syngas.
- **Air-blown vs. Oxygen-blown.** The supply of oxygen in gasification reactors is essential to produce high calorific value syngas. Oxygen can be delivered in gasification, through simply blowing natural air into the process or using high purity oxygen, produced by advanced cryogenic air separation units. Air-blown gasifiers tend to be more popular for smaller or lower temperature gasifiers (e.g., non-slagging) and are also far more affordable to operate. Gasifiers that are fed by air separation units operate at much higher costs but also produce a syngas with a calorific value up to three times that of air blown gasifiers.
- **Quench vs. Heat Recovery.** All gasification processes must cool exiting syngas (normally to approximately 100˚C) to apply standard acid gas removal technologies. Cooling and heat capture processes will normally pass through one of two cooling mechanisms. In the more advanced, and expensive cooling procedure, syngas will be cooled via a series of advanced heat exchangers (that can recover the heating value of the syngas for use in a steam cycle of an IGCC). In a lower cost and simpler mechanism, syngas will be cooled through contact with cool water (the “quench”

process"). While this latter option provides better CO_2 capture opportunities, it does not offer the same heat recovery potential of mechanized heat recovery systems and may therefore only be desirable where a lower quality or lower cost feedstock is used.

3.2 Technical Considerations and Challenges

Gasification technology designed for MSW feedstock presents several advantages as well as challenges that can include feedstock requirements, institutional support and permitting. Understanding these technical considerations and challenges can help communities determine the potential role of gasification technology in their local context.

Feedstock Supply and Preprocessing

Feedstock capacities for gasification facilities identified range from 20 to 100 tons per day. Gasification companies require specific waste streams for their feedstock that often need to be sourced and contracted from a mix of individual waste consignments such as MSW collection contractors (or municipalities), materials recovery facilities (MRFs), or construction and demolition waste contractors. The energy output and emissions produced by gasification is highly sensitive to the composition of the MSW feedstock and facilities will tailor the mix of MSW-derived feedstock to achieve desired levels of energy output and/or process emissions. High heating-value feedstock (e.g., plastics) generally will produce more energy output on a per ton basis than lower heating-value feedstock (e.g., organics).

Most gasification technologies require preprocessing of the MSW feedstock before it enters the gasifier. Preprocessing can include shredding, drying, and pelletizing. Companies profiled, such as Enerkem, Alter NRG, have such preprocessing requirements. The benefit of feedstock preprocessing is that it can improve the quality of the syngas as well as process byproducts to enhance the possibility of their reuse. Companies reviewed in this study specifically noted high moisture content and contamination levels (e.g., asbestos, contaminated wood, marine wood debris) as challenges.

3.3 MSW Gasification Facilities

Internet research yielded information to identify companies with gasification projects using MSW feedstock. **Figure 6** provides a map of the MSW gasification facilities in the US (and Canada) that are operating or in development stages and non-operational. **Table 3** provides additional information about these facilities.

These searches yielded 60 total studies that were included in the companion literature review Excel® tracking template. There were 48 studies conducted since 2012. After this initial search effort, the studies were scanned to determine the technologies and feedstocks assessed as well as the geographic location of the study. An evaluation was conducted to generate a short summary and a rating for the relevance of each study relative to the project scope using a low/medium/high scale. Examples of low relevance studies include those that did not evaluate the technologies of concern, provided no inventory data or used data from another source, or explicitly focused on developing countries. Examples of medium relevance studies include those that provide some parameters for the technologies of concern or provide significant data for related technologies which may be useful (e.g., 'combustion' or 'incineration'). A high relevance study is defined as one that provides significant data for the technologies of concern.

Twenty-three studies out of the sixty identified were deemed to be of medium and high relevance. LCI data from these studies was extracted and compiled in a Microsoft Excel workbook. Data compiled were subsequently harmonized in terminology (i.e., labeling of parameters) and normalized to common units (e.g., kg, L, mega joule [MJ]) per tonne of feedstock.

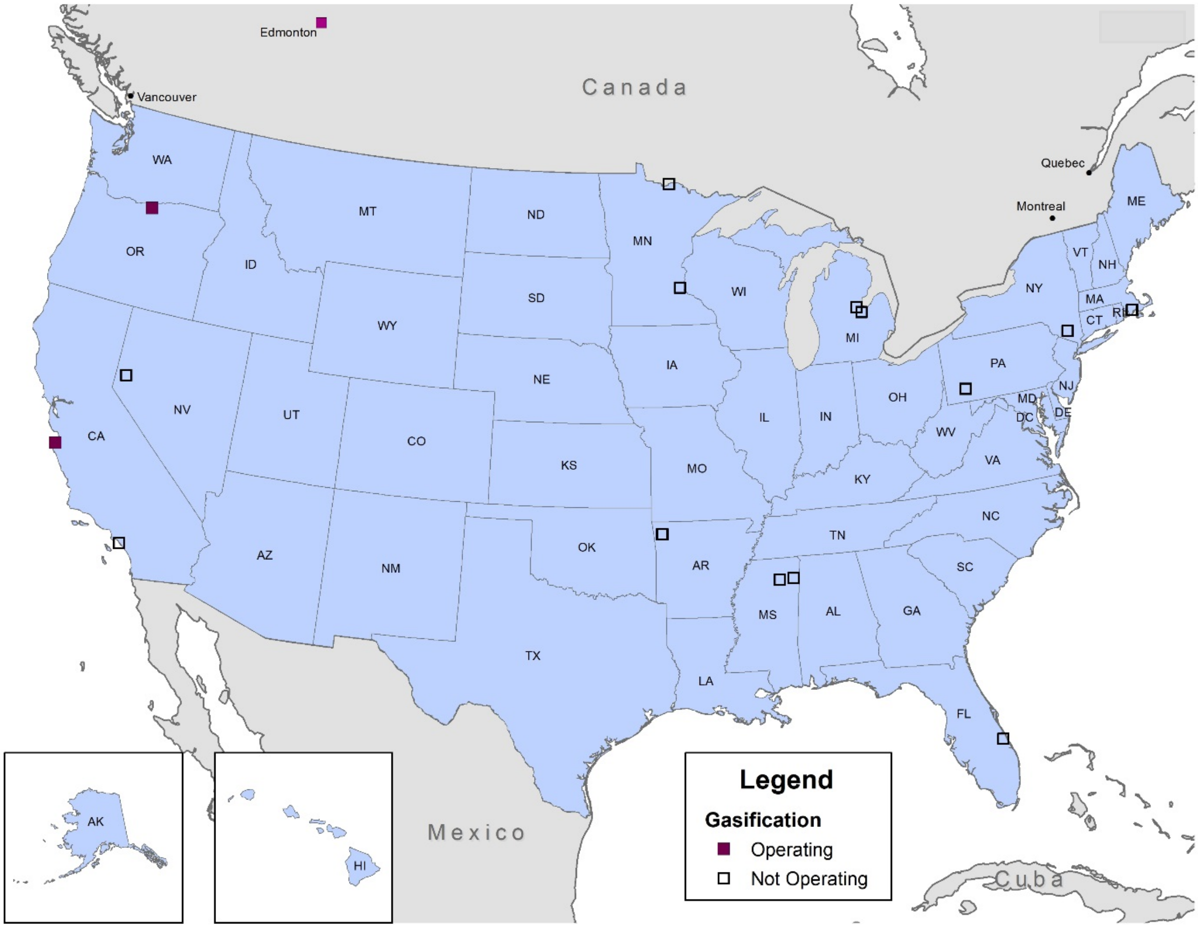


Figure 6. MSW gasification facilities.

Table 3. MSW Gasification Facilities

Name	City	State	Technology	Feedstock	Main Product	Operating Status
Operating						
Enerkem[35]	Alberta	Canada	Gasification	MSW	Ethanol	Operating 350 ton/day capacity facility.
Sierra Energy	Monterey	CA	Gasification	MSW	Syngas to electricity to diesel	20 ton/day capacity demonstration facility at Fort Hunter Liggett.[36]
In Development						
Fulcrum BioEnergy, InEnTec, LLC	McCarran	NV	Gasification	MSW	Syngas to diesel and jet fuel	Under construction. In September 2014, Fulcrum received a $105 million loan guarantee from the USDA as part of the Biorefinery Assistance Program. The feedstock processing facility, phase 1, has been operating since 2016. Construction of the biorefinery, phase 2, started in May 2018. The plant is expected to be operational in 2020.[37]
Not Operating or Unknown Operating Status						
Alter NRG	Madison	PA	Gasification	MSW	Syngas	Demonstration facility was retired in 2014.[38]
Cirque Energy LLC	Midland	MI	Gasification	MSW	Syngas to electricity and steam	Not built. The project was cancelled in 2012 due to market uncertainties.[39]

[35] Reports of this project describe it as being in disrepair and not operating at capacity.
[36] U.S. Army Garrison Fort Hunger Liggett The Golden Guidon. December 2017 *Sierra Energy Prepares to Turn on FastOx Gasification Plant at FHL.* https://www.dvidshub.net/publication/issues/36873
[37] Press Release – Fulcrum BioEnergy, Inc. *Fulcrum BioEnergy breaks ground on Sierra Biofuels Plant.* May 16, 2018 https://www.prnewswire.com/news-releases/fulcrum-bioenergy-breaks-ground-on-sierra-biofuels-plant-300649908.html
[38] Alter NRG. Projects http://www.alternrg.com/waste_to_energy/projects/ accessed as of 8/1/2018.
[39] Cirque Energy – Midland Power Station http://www.cirque-energy.com/projects/mps.html/ accessed as of 8/1/2018

Name	City	State	Technology	Feedstock	Main Product	Operating Status
Enerkem	Inver Grove Heights	MN	Gasification	MSW	Ethanol	Planning (anticipated construction 2020)[40]
Enerkem	Pontotoc	MS	Gasification	MSW	Ethanol	Not built. In 2010, DOE awarded $50 million in cost share funding to Enerkem, Inc. for the final design, construction, and operation of a proposed Heterogeneous Feed Biorefinery Project[41]
Entech Renewable Energy	Huntington Beach	CA	Gasification	n/a	n/a	Not built. In 2013 the project was placed on an indefinite hold due to economic and financial constraints.[42]
InEnTech/WM	Arlington	OR	Gasification	MSW	Hydrogen	Not operational.[43]
Ineos	Vero Beach	FL	Gasification	MSW, biomass	Ethanol	Ceased operations in 2016[44]. Received $125 million in federal grants and guaranteed loans. In 2012 the facility came online but had limited production due to technical challenges.[45]

[40] Star Tribune. Erin Adler. *Inver Grove Heights biofuel plant still on track, but hurdles remain.* July 21, 2018. http://www.startribune.com/inver-grove-heights-biofuel-plant-still-on-track-but-hurdles-remain/488810231/

[41] Enerkem, Inc. *Enerkem Awarded $50 Million Funding by U.S. Department of Energy for its Mississippi Biorefinery Project.* December 7, 2009. https://www.newswire.ca/news-releases/enerkem-awarded-50-million-funding-by-us-department-of-energy-for-itsmississippi-biorefinery-project-539048711.html

[42] Memo County of Los Angeles Department of Public Works. "Board Motion of April 20, 2010, item No. 44 Conversion Technologies in Los Angeles County Six-Month Status Update: October 2012 through April 2013 Update." April 29, 2013 http://dpw.lacounty.gov/epd/conversiontechnology/CT_6_month_report_cover_memo_To_Each_Supervisor_04-29-13.pdf

[43] Communication with Oregon DEQ. July 2019.

[44] Biomass Magazine. E. Voegele. *Ineos Bio to sell Ethanol Business, including Vero Beach Plant*. 2016. http://biomassmagazine.com/articles/13662/ineos-bio-to-sell-ethanol-businessincluding-vero-beach-plant.

[45] TC Palm. Lucas Daprile. *Investigation: INEOS failed despite $129 million in taxpayer subsidies.* January 17, 2017 https://www.tcpalm.com/story/news/2017/01/17/ineos-closes-vero-beach-biofuel-plant/96412616/

Name	City	State	Technology	Feedstock	Main Product	Operating Status
Taylor Biomass	Montgomery	NY	Gasification	MSW	Syngas to electricity	Not built. Seeking funding and in the conceptual phase since 2000.[46]
Westinghouse /Coronal/Alter NRG	International Falls	MN	Gasification	n/a	n/a	Not built. Planning began in 2008 and included more than $5 million for a feasibility study funded by US DOE and the Minnesota Pollution Control Agency.[47]
Ze-Gen	New Bedford	MA	Gasification	MSW	Syngas	Pilot facility closed in 2010.[48]

MSW, municipal solid waste; n/a, not applicable

[46] Times Herald-Record. Amanda Spadaro. *Taylor biomass project could get financing by Sept. 30*. July 6, 2017. https://www.recordonline.com/news/20170706/taylor-biomass-project-could-get-financing-by-sept-30
[47] International Falls Journal. Emily Gedde. *RECAP still on the radar.* May 9, 2017.
[48] Boston Business Journal. Kyle Alspach. *Ze-gen to halt New Bedford plant.* August 31, 2010.

Chapter 4: MSW Pyrolysis

Pyrolysis is defined as an endothermic process, also referred to as cracking, using heat to thermally decompose carbon-based material in the absence of oxygen. The main products of pyrolysis include gaseous products (syngas), liquid products (typically oils), and solids (char and any metals or minerals that might have been components of the feedstock). In the US, pyrolysis feedstock usually consists of mixed plastics or specific plastic resins and the resulting liquid petroleum-type products generally require additional refining. Pyrolysis feedstock can also include biomass (e.g., forest or agricultural residues). However, in the context of MSW, the likely feedstock will be plastics. Application of pyrolysis to MSW plastics generate a gaseous mixture of carbon monoxide (CO) and hydrogen called “syngas” that can be used for steam and electricity generation and some produce liquids such as a “crude oil” or heavy fuels. Products of processes are commonly reported, but the list and proportion of each differs depending on technology design, reaction conditions and feedstock.

4.1 MSW Pyrolysis Process Description

The literature and technology vendors use different names for pyrolysis (e.g., catalytic cracking) and different process variations which can cause confusion. Technological processes can be simplified into three core types of pyrolysis, including:

- **Thermal pyrolysis** —The feedstock is heated at high temperatures (350–900 ˚C) in the absence of a catalyst. Typically, thermal cracking uses mixed plastics from industrial or municipal sources to yield low-octane liquid and gas products. These liquid and gas products require further refining to be upgraded to useable fuel products.
- **Catalytic pyrolysis** —The feedstock is processed using a catalyst. The presence of a catalyst reduces the required reaction temperature and time (compared to thermal pyrolysis). The catalysts used in this process can include acidic materials (e.g., amorphous silica-alumina), zeolite minerals (e.g., HY, HZSM-5, mordenite), or alkaline compounds (e.g., zinc oxide). This method can be used to process a variety of plastic feedstock, including polyethylene terephthalate (PET), low-density polyethylene (LDPE, #4), high density polyethylene (HDPE, #2), polypropylene (PP, #5), and polystyrene (PS, #6). The resulting products can include liquid and gas products that require further refining to be upgraded to useable fuel products.
- **Hydrocracking (sometimes referred to as “hydrogenation”)**—The feedstock is reacted with hydrogen and a catalyst. The process occurs under moderate temperatures and pressures (e.g., 150–400°C and 30–100 bar). Most research on this method has involved generating gasoline fuels from various waste feedstocks, including MSW plastics, plastics mixed with coal, plastics mixed with refinery oils and scrap tires. The resulting products can include liquid and gas products that require further refining to be upgraded to useable fuel products.

4.1.1 General Process Flow

Despite the variations in operating cost, efficiency and processing capacity among the technologies profiled in this report, most pyrolysis technologies follow a general process flow, described below and illustrated in **Figure 7**.

1. **MSW Feedstock:** Feedstocks can include processed/treated (e.g., presorted, preprocessed plastics) or unprocessed MSW. Depending on the specific feedstock(s) accepted and/or received, preprocessing at pyrolysis facility may be required or the feedstock is used as-is and directly fed into the processing line.
2. **Preprocessing:** Preprocessing may be required and can include shredding, sorting, washing

and/or drying to ensure the feedstock meets the specifications of the technology. For example, non-recyclable plastics waste that has already been sorted at a MRF may need to be shredded into smaller (.25" to 2") particles to ensure complete combustion or meet the design specifications.

3. **Densification:** In some cases, the feedstock is low-density and thus it is processed into a higher density material (e.g., pellets, cubes). Such densification may be done to increase the caloric value per unit of volume, provide greater uniformity, and/or simplify storage and mechanical feeding of the feedstock. This is particularly useful in processing low-density plastics such as film plastics[49] (i.e., outer protective covering or film).

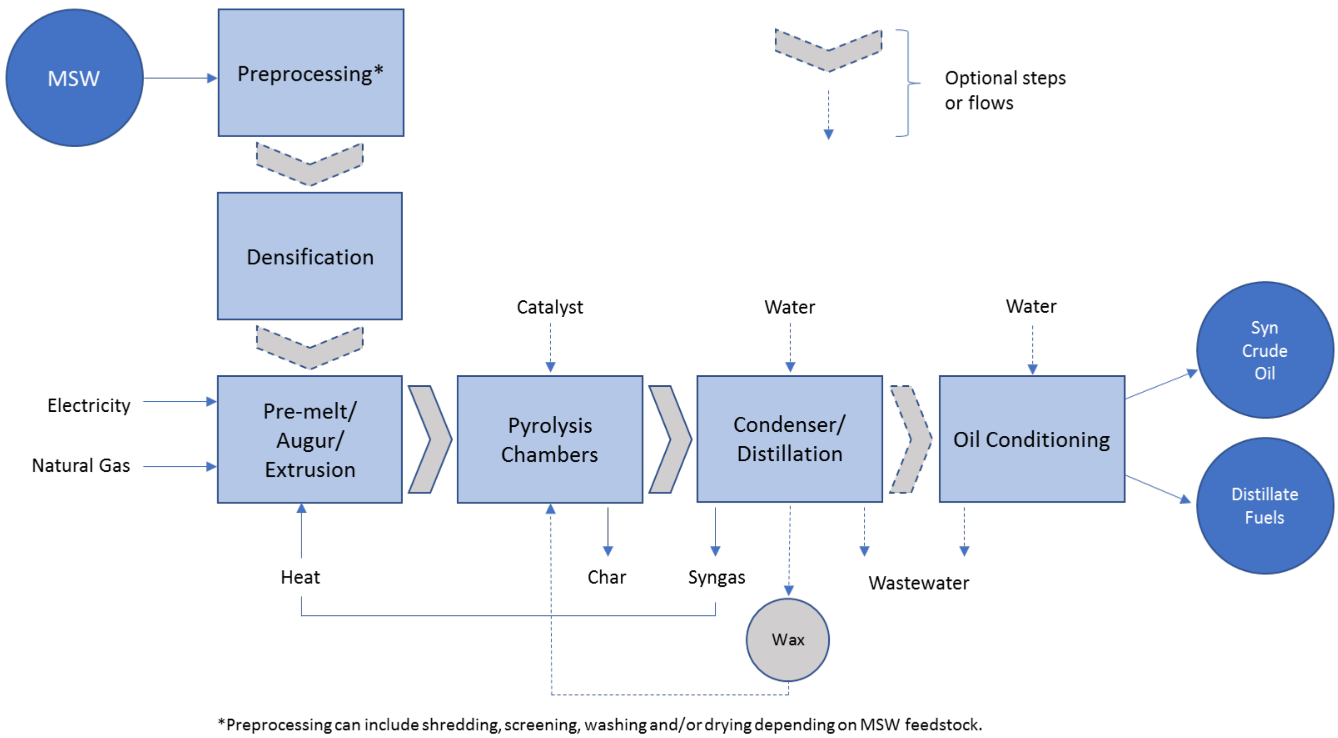


Figure 7. General pyrolysis process flow diagram.
(Source: adapted from ACC, 2015)

4. **Pre-melt / Auger / Extrusion:** When necessary, pre-melting of plastic feedstock is done to create a more homogeneous mixture and consistent feedstock. This process uses mechanical energy and heaters, normally extruded through a rotating screw (auger) to create a consistent volume of feedstock for input to the pyrolysis chamber(s).

5. **Pyrolysis Chambers / Pyrolysis:** Once the feedstock is fed into the pyrolysis chambers, it is rapidly heated at high temperatures and in certain cases (e.g., catalytic pyrolysis) mixed with a catalyst. Specific pyrolysis applications that take place in the pyrolysis chambers include:

[49] Plastic film is defined and described well at this website: https://www.grafixplastics.com/plastic-film-what/

- **Thermal Pyrolysis** involves degradation of plastic feedstocks using high temperature (ranging from 350–900 °C in the absence of air).
- **Catalytic Pyrolysis** involves degradation of plastic feedstocks in the presence of a catalyst and in the absence of air.
- **Hydrocracking** involves degradation of plastic feedstocks by reacting them with hydrogen and a catalyst. The process occurs under moderate temperatures and pressures (e.g., 150–400 °C and 30–100 bar).

Pyrolysis operators can also tailor the speed at which plastic feedstock is heated once fed into the pyrolysis chambers, with two general variations which include *fast or slow* pyrolysis. Fast pyrolysis entails rapid heating of feedstocks to approximately 500 °C in less than one or two seconds, whereas slow pyrolysis can take several hours. Pyrolysis vapors are rapidly quenched and captured. In slow pyrolysis, the process is characterized by lengthy feedstock and gas residence times, low temperatures and slow heating rates. Heating temperature rates range from 0.1–2 °C per second and the prevailing temperatures are nearly 500 °C.

6. **Catalyst:** For catalytic pyrolysis, additives help to reduce required pyrolysis temperature and reaction times (as compared to thermal pyrolysis). Catalysts additionally produce a higher value hydrocarbon (e.g., leading to greater efficiency and value of the pyrolysis fuel products). While catalyst data from profiled companies was in most cases, proprietary, several conventional heterogeneous catalysts have long been employed in pyrolysis, that include solid acids (such as zeolites, silica-alumina, alumina) and fluid catalytic cracking catalysts, mesostructured catalysts, nanocrystalline and zeolites.
7. **Distillation:** Primary pyrolysis oil is fed into a distillation plant, where it is heated in the absence of oxygen. Vapors from the boiling oils are condensed into liquid fuels via a cooling pipe, and then separated through a water bubbler vaporizer. Distillation is carried out to separate the lighter and heavier fractions of hydrocarbons present in the pyrolysis oil. The distillation is operated between 116 °C and 264 °C approximately 73.5% of pyrolysis oil is distilled out.
8. **Oil Conditioning:** Oil conditioning encompasses different processes necessary to stabilize oil end products from volatile materials which allows them to be available for the markets. Oil conditioning processes may include fractionation, distillation, hydrogenation and water treatments.

4.1.2 Process Variations

Among the variations that exist in pyrolysis, key challenges and considerations relevant to the technology can be broken by preprocessing, processing and post-processing steps.

Preprocessing (Feedstock Quality Control)

The relationship between pyrolysis operators and feedstock suppliers, in respect to preprocessing requirements, is strongly highlighted in this report. Companies either depend on securing tailored and consistent quality feedstock from their suppliers for a higher delivery fee or invest in enhancing their own preprocessing capacity. Fine-tuning the quality of feedstock was, for most companies, essential to realizing a financially feasible business operation. Key risk factors in feedstock included: the chip size of feedstock (after shredding of feedstock); the mitigation of contaminants in the feedstock (wood, metal, soil, fiber contaminants); and the removal of non-target plastics, most regularly cited as PET due to high oxygen content and combustion risks, and polyvinyl chloride (PVC) due to combustion risks and chloride lead to the formation of dioxin and acid gases.

If a company decides to invest in in-house capacity for preprocessing equipment, they must consider the range of resources that this machinery may require including: water (to condense syngas vapors, oil conditioning), natural gas (to initiate systems), hydrogen (sulfur, nitrogen and aromatic reduction; enhancement of cetane number, density and smoke point), and catalysts (normally proprietary) to trigger the reaction. While many of these resources are necessary in pyrolysis applications—regardless of whether a feedstock supplier is involved in preprocessing activities—the quantity, efficiency and applications of these resources differ.

In two unverified case examples, Nexus Fuels reported that it could only accept feedstock levels that contain under 1% of PVC, in comparison with Renewlogy (formerly PK Clean) that can accept up to a 40% mix of PVC and PET in feedstock (ACC, 2015). While Nexus Fuels and Renewlogy differ in the type of pyrolysis they employ (hydrocracking pyrolysis and catalytic pyrolysis respectively), the report notes that Renewlogy has invested substantially in enhancing its own proprietary technology and catalyst to accept a broader range of plastic sub-typologies and reduce long-term operational costs.

Processing (Continuous vs. Batch Processing)

The ability of pyrolysis technology vendors to achieve higher fuel production and heat retaining efficiency from their operations can depend on whether they operate a continuous or batch feedstock system. Batch feedstock systems normally require companies to insert tailored quantities of specific plastic feedstock into their processing lines at pre-determined intervals. The insertion of plastic feedstock normally must complete its processing cycle, before a new insertion can be made—often requiring companies to start and stop their machinery and lose out on sustained heat efficiency in their processing lines. Companies operating a continuous feedstock system, by comparison, are normally capable of capturing and retaining the heat value from produced hydrocarbons in their production lines (e.g., avoiding batch operation systems, where reactors constant heating and cooling procedures require constant reboots and energy losses). In an unverified case example of the efficiency differences between batch and continuous feedstock systems, Renewlogy claimed that their pyrolysis technology costs a quarter the price of competing systems to operate, while producing greater yields due to their ability to sustain heat value from produced hydrocarbons for continuous plastic processing.

Post-Processing (Indirect Outputs of Pyrolysis)

Several pyrolysis companies profiled in this report identified key considerations arising from the indirect outputs of pyrolysis that either posed waste management challenges or challenges associated with identifying markets for the sale or reuse of product outputs. Specific outputs included:

- **Char:** Char (also referred to as biochar) is considered a hazardous waste and specific licensing (e.g., waste disposal licensing) and approvals are often required for its disposal. This results in higher costs and challenging administrative hurdles that companies must face, should they not be able to reuse the char or mitigate its production internally.
- **Wax:** Wax production (normally less than or equal to 10% by weight of incoming useable feedstock) was cited as a challenge by some companies where: wax was either unable to be processed into a marketable end product; where markets for processed wax products could not be identified; or where wax products could not be reused in the processing line internally.
- **Synthetic Crude Oils:** Syncrude is a primary output of pyrolysis, which likely will require additional refining or cleaning to meet market requirements. Certain companies, including Nexus Fuels encountered difficulties via delayed quality testing of their fuels due to the delayed installation of a commercial fractionation system. They additionally faced difficulties in marketing synthetic crude oil to refineries—respectively requiring the company to make plans to either reuse or store their fuel on-site.

4.2 Technical Considerations and Challenges

Thermal and catalytic pyrolysis of MSW-based feedstock present several technical considerations and challenges including feedstock typology challenges, feedstock quality and preprocessing requirements, net energy balance, institutional support, and permitting. Understanding these technical considerations and challenges can help communities determine the potential role of pyrolysis technology in their local context.

4.2.1 Typology Considerations

Many different types of plastics are generated, and often mixed, as part of MSW. The inconsistency in plastic composition and difficulty in anticipating the market trends of manufacturers can increase the cost of fuel production by pyrolysis operators, while presenting greater challenges to companies in managing and mitigating the impacts of chlorine (equipment corrosion) and char (hazardous waste management).

Specific considerations and challenges regarding common types of plastic are discussed below.

- HDPE and LDPE: These plastics perform differently with respect to whether a thermal or catalytic pyrolysis is being employed. Thermal pyrolysis normally yields much higher wax content from HDPE and LDPE feedstock, reducing the amount of liquid oil produced. Catalytic pyrolysis, in comparison, normally achieves a full conversion of HDPE and LDPE to oil with minimal yields of wax produced[50]. However recovery of the catalyst can be a significant issue.
- PET: The strong recycling market value for PET can result in this plastic being removed from MSW and supply streams, potentially limiting its availability for pyrolysis. PET contains high levels of oxygen that can lead to combustion in the pyrolysis reactor and can also contain heteroatoms, which can create challenges in standard pyrolysis. Hydrocracking pyrolysis removes heteroatoms, which form oil resources, while conserving catalysts. Hydrocracking pyrolysis is a widely employed practice to avoid challenges associated with PET pyrolysis and is additionally beneficial in requiring lower process temperatures and in producing higher quality fuels that do not normally require further treatment for conversion[51].
- PS: Typically, PS will produce a less viscous oil in both thermal and catalytic pyrolysis—resulting it in being the most preferred waste typology by all reviewed companies in this study[52].
- PVC: This plastic typology produces hazardous chlorine gas in both thermal and catalytic pyrolysis applications. The presence of chlorine and the deposition of coke additionally affect the catalytic activity of the catalyst. PVC also contains dioxin-producing chlorides and can lead to the formation and emission of hydrochloric acid (HCL). HCL emissions are often corrosive when processed in pyrolysis technology and can be both expensive and labor intensive to remove.
- Other: A variety of other factors relevant to other types of plastics can present challenges to pyrolysis technologies. These include: (1) inclusion of corrosive chlorines as flame retardants or fillers by plastic manufacturers that can normally only be detected utilizing burn tests; (2) the

[50] Rashid, M. et al., (2016). Catalytic Pyrolysis of Plastic Waste: A Review. Available at: https://www.researchgate.net/publication/304629166_Catalytic_Pyrolysis_of_Plastic_Waste_A_Review
[51] Nzerem, P. C., (2013). Rheological Studies of Feedstock for the Hydrocracking of Waste Plastics. https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:215058&datastreamId=FULL-TEXT.PDF
[52] Rashid, M. et al., (2016). Catalytic Pyrolysis of Plastic Waste: A Review. Available at: https://www.researchgate.net/publication/304629166_Catalytic_Pyrolysis_of_Plastic_Waste_A_Review

production of multi-layer plastics; and (3) the frequent changes of plastic compositions by plastic manufacturers for cost, marketing and branding purposes.

4.2.2 Feedstock Requirements and Dependence

Pyrolysis companies have a strong reliance on securing consistent and quality-controlled feedstock, and often indicate that the lack of formal feedstock partnerships as a challenge. Companies reviewed as part of this study presented various means of securing feedstock requirements through both public and private sector channels. Specific examples include:

- Nexus Fuels: to move beyond a pilot stage requires that a strategic project partner provide a feedstock guarantee, with tax incentives, grants and labor provisions considered beneficial.
- Vadxx Energy LLC: dropped plans to invest in Cleveland, Ohio after the city of Akron, Ohio provided more attractive tax and support incentives. It additionally signed a memorandum of understanding with Houston-based Greenstar Recycling to provide raw material inputs for Vadxx's first commercial plastics-to-oil unit.
- GEP Fuel: established close networks with the auto industry and conducted market research to identify high levels of consumer plastic waste production in Carroll County, Indiana. It additionally partnered with an existing rail network, owned by US Rail Corp, that is planned to assist in the transport feedstock and product for the company.

In addition to securing consistent and clear agreements with public or private feedstock suppliers, companies had clear preferences to the types of plastics[53] they received as inputs. Companies profiled overwhelmingly preferred the processing of Plastics 2 and sometimes 4, citing the lower energy rates and poorer quality control of Plastics 5–7 (particularly film plastics). Vadxx Energy for example noted that much of the plastic types (4–7) they received, contained additives and fillers that made them incompatible or difficult to use as feedstock.

4.3 MSW Pyrolysis Facilities in the US

Internet research yielded information to identify companies with pyrolysis projects using MSW feedstock. **Figure 8** provides a map of the MSW pyrolysis facilities in the US (and Canada) that are operating or that are in development stages and non-operational. **Table 4** provides additional information about these facilities.

[53]Plastic resin codes can be found here: https://plastics.americanchemistry.com/Plastic-Resin-Codes-PDF/

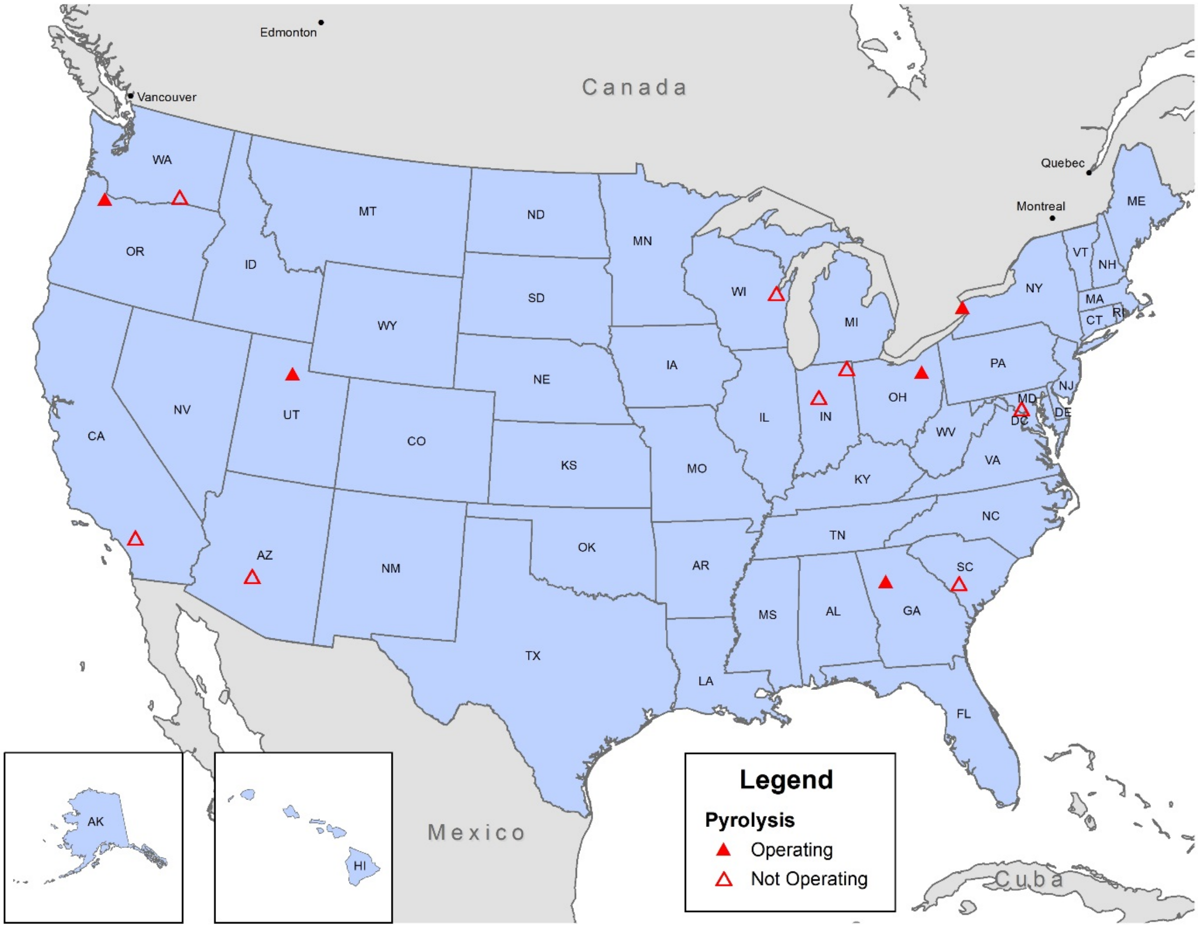


Figure 8. MSW pyrolysis facilities.

Table 4. Pyrolysis Facilities Operating on Plastics from MSW

Name	City	State	Technology	Feedstock	Main Product	Operating Status
Operating						
Agilyx	Tigard	OR	Pyrolysis	PS	Styrene oil	Operating. In 2013, the Tigard facility processed plastics to crude oil. It went dormant. In 2018, it reopened a 10 ton/day capacity facility for converting polystyrene to styrene oil.[54]
JBI / Plastics2Oil	Niagara Falls	NY	Pyrolysis	HDPE, LDPE, PP	Fuel oil #2, fuel oil #6	Operating at limited production of its 22 ton/day capacity as of August 2018.[55] In 2014, the facility suspended its plastic processing and fuel production operations.[56]
Nexus Fuels	Atlanta	GA	Pyrolysis	HDPE, LDPE, PP, PS	Gasoline, diesel Gasoline	Operating on a discontinuous basis. Has a stated capacity of 50 tons/day.
Renewlogy	Salt Lake City	UT	Pyrolysis	Mixed plastics	Naptha, diesel fuel, kerosene, light fuels	Has a stated capacity of 10 tons/day. Operations paused for most of 2019 as the facility upgraded its preprocessing equipment.[57]
In Development						
Brightmark Energy/ RESpolyflow	Ashley	IN	Pyrolysis	Mixed plastics	Naptha, diesel fuel, waxes	Under construction which began in 2019.[58] In the planning phase since 2015. In 2018, the Steuben County Board of Commissioners loaned RES Polyflow

[54] Press Release from Agilyx. *Agilyx opens the world's first commercial waste polystyrene-to-styrene oil chemical recycling plant.* April 24, 2018. https://www.agilyx.com/application/files/6015/2510/8377/agilyx_opens_tigard_plant.pdf

[55] Press Release from Plastic2Oil. *Plastic2Oil Announces Plan to Resume Fuel Production and Sales and Amends Veridisyn Agreement.* August 10, 2018. http://www.plastic2oil.com/site/news-releases-master/2018/08/10/plastic2oil-announces-plan-to-resume-fuel-production--sales-and-amends-veridisyn-agreement

[56] Accesswire. *Letter to Plastic2Oil Stockholders from Richard Heddle, Chief Executive Officer.* November 24, 2014. https://finance.yahoo.com/news/letter-plastic2oil-stockholders-richard-heddle-150000520.html

[57] WasteDive. Pyzyk, Katie. *Boise, Idaho mixed plastics program could expand following changes.* July 24, 2019. https://www.wastedive.com/news/boise-idaho-mixed-plastic-program-could-expand-following-changes/559418/

[58] Recycling Today. Cottom, Theresa. Brightmark Energy breaks ground on plastics-to-fuel plant. 22 May 2019. https://www.recyclingtoday.com/article/brightmark-energy-plastics-to-fuel-groundbreaking/

Name	City	State	Technology	Feedstock	Main Product	Operating Status
						$1.5 million and offered them a 10-year tax abatement for the facility to be built near Ashley.[59]
Renew Phoenix/ Renewlogy	Phoenix	AZ	Pyrolysis	Mixed plastics	Naptha, diesel fuel, kerosene, light fuels	In the planning stage for a facility in Phoenix, AZ. Expected to be operational in 2020. In 2019, the Phoenix Public Works Department chose Renew Phoenix for a 10-year contract.[60] Renewlogy was awarded a grant through the Arizona Innovation Challenge.[61]
Rialto Bioenergy	Rialto	CA	AD and pyrolysis	Food waste, municipal biosolids	Biochar (fertilizer)	Under construction. The anaerobic digester is expected to be operational in 2020.[62] Pyrolysis unit included in design.
Not Operating or Unknown Operating Status						
Climax Global Energy	Blackwell	SC	Pyrolysis	Mixed plastics	Syncrude, petrochemicals	Never started operations and defaulted on its rent to Barnwell County.
Envion	Derwood	MD	Pyrolysis	n/a	n/a	Never built. In 2012, Envion owner, Michael Han was convicted of fraud.[63]
GEP Fuel & Energy	Camden	IN	Pyrolysis	Mixed plastics	Diesel fuel	Not built. Planning began in 2016.

[59] Indiana Economic Digest. Mike Marturello. *RES Polyflow ties up loose ends with Steuben County in quest for funding.* July 18, 2018. https://indianaeconomicdigest.com/main.asp?SectionID=31&SubSectionID=67&ArticleID=92832
[60] WasteDive. Pyzyk, Katie. Phoenix awards contract to Renewlogy for chemical recycling project. 5 April 2019. https://www.wastedive.com/news/phoenix-awards-contract-to-renewlogy-for-chemical-recycling-project/552055/
[61] TechConnect. *Arizona Innovation Challenge Fall '17: Transforming Plastic into Clean Fuel.* April 3, 2018.
[62] Anaergia Launches Rialto, Calif., Food Diversion, Energy Recovery Plant. 12 Mar 2019. https://www.waste360.com/anaerobic-digestion/anaergia-launches-rialto-calif-food-diversion-energy-recovery-plant
[63] Palm Beach Post. Jeff Ostrowski. *Former defense secretary says West Palm Beach business man defrauded him of $32 million.* October 18, 2012. https://www.palmbeachpost.com/news/former-defense-secretary-says-west-palm-beach-businessman-defrauded-him-million/pLoHwoEKze3ohKLM5htxbO/

Name	City	State	Technology	Feedstock	Main Product	Operating Status
Green Power Inc	Pasco	WA	Pyrolysis	n/a	n/a	Not operating. In 2009, Washington State ordered it to stop because it lacked the necessary air-quality permits.[64] In 2015, the CEO, Michael Spitzauer, was convicted of fraud.[65]
International Environmental Solutions	Romoland	CA	Pyrolysis	n/a	n/a	The pilot facility ceased operations in 2010. In 2012, International Environmental Solutions declared bankruptcy.
New Hope	Tyler	TX	Pyrolysis	HDPE, LDPE, PP, PS	Fuel oil #2, fuel oil #4	Unknown.
Oneida Seven Generations Corporation	Green Bay	WI	Pyrolysis	n/a	n/a	Not built. In 2018, the City of Green Bay will pay the Oneida Seven Generations Corporation $2.5 million in a legal settlement.[66]
Vadxx	Akron	OH	Pyrolysis	Mixed plastics	Diesel oil, naphtha, syngas, waxes	Not operating. Operated a bench scale model for a short time in 2017.[67]

MSW, municipal solid waste; n/a, not applicable, HDPE, high density polyethylene; LDPE, low density polyethylene, PP, polypropylene; PS, polystyrene

[64] Associated Press. Phuong Le. *Waste-to-fuel project CEO accused of fraud; Cheyenne plant never materialized.* January 9, 2014. https://trib.com/business/energy/waste-to-fuel-project-ceo-accused-of-fraud-cheyenne-plant/article_0e6ca24a-0d18-5175-affe-4a9626a3cd09.html
[65] Tri-City Herald. Kristi Pihl. *Green Power founder sentenced in 'sophisticated' $13 million fraud.* June 10, 2015. https://www.tri-cityherald.com/news/local/crime/article32228337.html
[66] USA Today Network-Wisconsin. Jonathan Anderson. *Green Bay to pay $2.5 million to settle lawsuit over waste-to-energy plant.* February 12, 2018. https://www.greenbaypressgazette.com/story/news/2018/02/12/green-bay-pay-2-5-million-settle-lawsuit-over-waste-energy-plant/328895002/
[67] Communication with Ohio EPA July 2019.

Chapter 5: MSW Anaerobic Digestion

AD is the biochemical decomposition of organic matter into methane (CH_4) gas and CO_2 by microorganisms in an anaerobic environment. The process does require any input heat source. Byproducts include air emissions and also solid and/or liquid digestate. The anaerobic processes occur naturally and are the principal processes by which methane is created from organics in landfills. The same basic process occurs in a more controlled environment of an anaerobic digester facility. The anaerobic digester is a built system for excluding oxygen from organic material and producing biogas. The biogas produced from an AD facility can be used directly to generate electrical energy or can be additionally treated to allow injection into the pipeline. The solid and liquid digestate can be land applied, composted, used as a soil amendment or processed into fertilizer pellets. The liquid digestate can be further processed to concentrate nitrogen or phosphorous chemicals. These chemicals can be sold outright or added to fertilizers.

5.1 Anaerobic Digestion Process Description

AD technologies can be grouped into two basic classes: wet (liquid) and dry (solid). Common design types for AD systems include:

- **Single-stage wet digesters:** Single-stage wet digesters include one vessel (or a series of single vessels). These systems are simpler to design, build, and operate and generally less expensive to build and operate. The loading rate for single-stage digesters is limited by the ability of methanogenic organisms to tolerate the sudden decline in pH that results from rapid acid production during hydrolysis. Hydrolysis is the first stage of the chemical reactions that occur in the anaerobic digestion process.
- **Single-stage dry digesters:** Single-stage dry digesters where the feedstock is in a solid state (i.e., can be handled with a front-end loader and is considered stackable) and normally little or no additional water is added. The digestion process can be done in a batch or continuous mode. In batch mode, feedstock is loaded into chamber(s) and held until the end of its retention time (30-45 days). The liquid digestate stream is usually captured and recirculated throughout the retention time. In continuous mode, new feedstock is continuously fed to the digester and digestate is continuously removed, additional liquids may be added as needed.
- **Two-stage digesters:** Two-stage AD systems separate the acid-producing fermentation process from the methanogenesis process, which allows for higher loading rates for high nitrogen containing materials. Total solids concentration in the reactor is an important variable and feedstock is typically diluted with process water during the preprocessing phase to ensure the desirable solids content is achieved.
- **Water Resource Recovery Facilities:** In the US, the use of AD at WRRFs, also known as publicly owned water treatment works, dates back to the 1900s. Over 1,200 US WRRFs produce clean water and these facilities have anaerobic digesters that treat wastewater solids and produce biogas. While a number of these WRRFs flare-off the biogas produced in this process, more than half use the biogas they produce as an energy resource for producing electricity or usable heat. Of the facilities using their biogas for energy, about one third are generating electricity that is used for operations at the facility. Of the WRRFs generating electricity from biogas, almost 10 percent sell this electricity to the grid. About 3 percent of the WRRFs with digesters process the biogas into a form that is pure enough to inject into natural gas pipelines. [Note**:** AD at WRRFs is not covered in detail in this report because it is does not involve new conversion technology facilities and the use of AD at WRRFs has become quite widely established.]

5.1.1 General Process Flow

Although there are many different design and configuration options, the AD process for MSW feedstocks is illustrated in **Figure 9** and generally consists of the following steps:

1. **MSW Feedstock:** AD systems typically rely on source separated organic MSW feedstock can include pre and post-consumer food waste, fats oils and greases, yard trimmings and paper products.

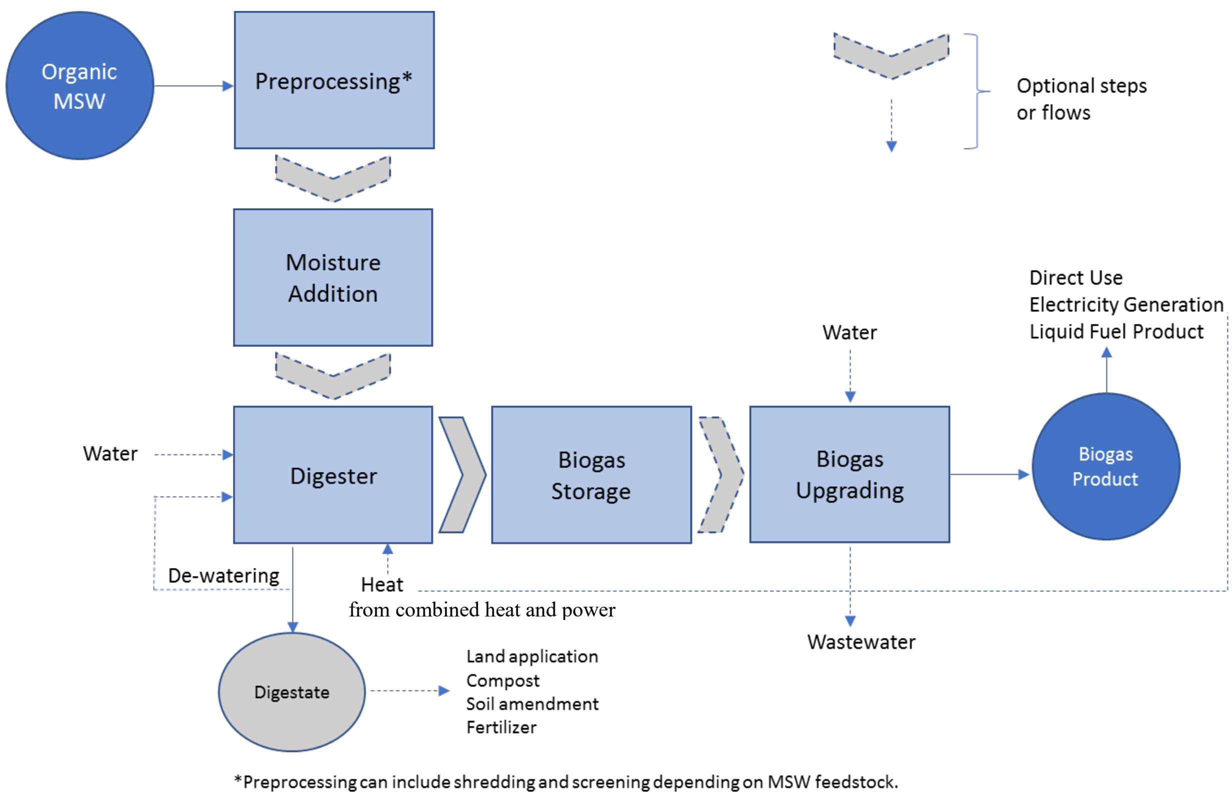


Figure 9. General single-stage MSW anaerobic digestion process flow diagram.

2. **Preprocessing**: Preprocessing of the MSW feedstock can include shredding and screening to remove any unwanted materials. Even if source-separated organics are received, they will likely require preprocessing to remove any metal, plastic and other contaminants, including packaging materials.

3. **Digestion:** The organic feedstock and various types of bacteria are put in an airtight container called a digester. Within the digester, the digestion process occurs and includes the following four phases:

   - **Hydrolysis:** Large proteins, fats and carbohydrates are broken down into amino acids, long-chain fatty acids, and sugars with the interaction of water.
   - **Acidogenesis:** The process by which simple monomers are converted into the volatile fatty acids, such as lactic, butyric, propionic, and valeric acid. This phase is also known as the fermentation step.

- **Acetogenesis:** The process by which the bacteria consume the fermentation products and create acetic acid, CO_2, and H_2.
- **Methanogenesis:** The process by which the organisms consume the acetate and it is converted into CH_4 and CO_2 while H_2 is consumed.

4. **Biogas Storage:** Biogas generated from the digester(s) will be collected and piped to a storage tank for use or further upgraded.
5. **Solid Digestate Handling**: Digestate resulting from the AD process may require dewatering to be directly land applied or to be aerobically cured into a mature compost product. The digestate may also be used as a soil amendment or as an ingredient used to produce fertilizer. If there is no end market/use for the digestate, it will require disposal. Water recovered from dewatering may be fed back into the digester or treated before discharge. If the water is being discharged to a sanitary district, pretreatment of the wastewater may be necessary.
6. **Liquid Digestate Handling:** Liquid digestate streams that contain significant amounts of nutrients (phosphorous, nitrogen or potassium) may be further processed into marketable products. Some of the technologies to recover or remove these elements include membrane separation, evaporation, and precipitation.

5.1.2 Process Flow Variations

Standard AD processes can be tailored to end-use needs, allowing for both large scale operations that meet nationwide energy needs (e.g., more than 1 MW equivalent) and small on-site energy production requirements (e.g., 25-250 KW equivalent). Under proper management, storage capacity and the optional identification of markets, a range of AD byproducts can provide additional revenue streams for operators. Common byproducts such as digestate solids, fiber or biofiber (contained in the effluent of common AD technologies) can be used in a range of applications including as organic fertilizer, livestock bedding, compost, fuel pellets, and construction materials such as fiber boards and composite materials.

Feedstock Processing

Feedstock processed in primary and (optional) secondary digesters may serve different purposes at a later output stage based on the technologies that are being employed by the specific plant (e.g., sludge and biogas dryers, combined heat and power plants, gas upgrading technology).

Specific variations in both the outputs of digestate and biogas may include:

- Digestate: A liquid filtrate (e.g., liquid fertilizer) or solid fiber output that may be used as compost, animal bedding, fiberboard. Digestate is produced by the AD separator system and sourced from the feedstock slurry.
- Biogas: Biogas derived fuels (e.g., methane) in addition to heat and steam that can be applied to gas burners and boilers (e.g., for space heating); turbines and generators (e.g., to produce both heat and power); or compressed and refined (e.g., to produce a higher-grade vehicle/transport fuel).

Biogas Upgrading

Depending on the end-use for the biogas, particularly for pipeline injection or vehicle fuels, upgrading of the biogas may be necessary. The goal of upgrading is generally to remove carbon dioxide to increase the methane concentration of the biogas. Depending on the feedstock and the system design, biogas is typically 55 to 75 percent methane (natural gas contains 99 percent methane). Upgrading also removes contaminants such as hydrogen sulfide and siloxanes using water-based scrubber systems or techniques (e.g., membrane separation, activated carbon).

The resulting biogas product can be used directly, combusted in a turbine or internal combustion engine to generate electricity or converted to a liquid fuel product. If used to generated electricity, combined heat and power systems can be employed where the heat from the combustion of biogas is captured and can also be used to heat nearby buildings and/or the digester.

5.2 Technical Considerations and Challenges

AD of MSW presents several technical considerations and challenges that can include feedstock pre-treatment requirements, process optimization, economies of scale, institutional support and socio-economic aspects. Understanding these technical considerations and challenges can help communities determine the potential role of AD technology in their local context.

5.2.1 Feedstock Supply and Preprocessing

The removal of inorganic materials (e.g., glass, plastic, metal, sand), wood waste, bone waste, soil and chemical contaminants (e.g., pesticides, antibiotics) from AD feedstock can be a challenge to ensuring optimal processing in the reactor. This may particularly be true for large scale AD operators who rely on feedstock that originated from mixed MSW (from local municipal partnership). Undesirable and contaminant feedstock led to clogging of pumps, contamination and poor biogas production. The most commonly practiced presorting and pretreatment activities consisted of particle size reduction, seeding, addition of metals, thermal and thermochemical pretreatment, ultrasonic pretreatment and alkali pretreatment.

5.2.2 Process Optimization

The constant and intensive task of monitoring and maintaining optimal chemical conditions of AD during processing was highlighted by companies as a key challenge to ensuring optimal biogas and digestate production. Specific chemical challenges noted by companies included the level of ammonia produced during processing (e.g., from poultry litter) and hydrogen sulfide that can break down the concrete structure of tanks and reduce the biogas and heat production. Key monitoring activities focused on the pH, nitrogen, methane, volatile fatty acids, alkalinity, ammonia concentration, and retention time of AD processing.

Companies such as Zero Waste Energy Development Company (ZWEDC) highlighted the importance of contamination in their feedstock, noting their right to refuse any incoming load of feedstock that contained more than 30% paper and/or fiber materials and more than 0.25% glass. Other companies, such as CR&R invested in magnet and eddy current separator technology that removes ferrous and nonferrous metals as well as a grinder that size reduces the feedstock to less than 2 inches for optimal plant performance.

5.2.3 Large vs. Small Scale Operations

The administrative and logistical hurdles that small and large AD operators comparatively encounter, presents a notable distinction in applicable challenges of AD processes. For example, small-scale AD plants that process up to 7,500 tons per year and produce approximately 25-250 Kw(e) often source their feedstock on-site for convenience and at little to no transport and logistical cost.[68] By comparison, large-scale AD plant can process 30,000 tons or more per year and may serve nationwide energy demands above 1MW1Mw(e)[69] commonly depend on quality-controlled feedstock arrangements from transport

[68] https://www.globalmethane.org/documents/AD-Training-Presentation_Oct2016.pdf
[69] https://www.globalmethane.org/documents/AD-Training-Presentation_Oct2016.pdf

and logistical suppliers of MSW and organic waste, prior agreements for feed in tariffs and power grid connections, and partnerships with key technology providers to ensure the maintenance of the plant.

J.R. Simplot Potato Processing Plant and the American Crystal Sugar Company noted the importance of establishing AD plants near both large urban metropolitan areas and agriculture production rich geographies. Companies depend on well-developed collection routes for the aggregation of agricultural food losses, excess prepared food, food scraps, and food manufacturing byproducts to realize an economically feasible operation.

5.3 Anaerobic Digestion Facilities

Companies and operators of AD facilities that accept MSW feedstock (food waste) were identified via an information collection request conducted by EPA (US EPA 2018). The EPA survey included facilities that are stand-alone and co-digestion, including as waste-water treatment plants (WWTPs) and on-farm digesters. For this report, the primary focus is stand-alone AD facilities.

Figure 10 provides a map of operating and not operating stand-alone and multi-source AD facilities in the US. **Table 5** lists the facilities. A full listing of AD facilities including industrial facilities and WTTPs using excess digester capacity MSW feedstock is provided in Attachment B and is available along with a listing of on-farm digestors in the EPA (US EPA 2018b) report.

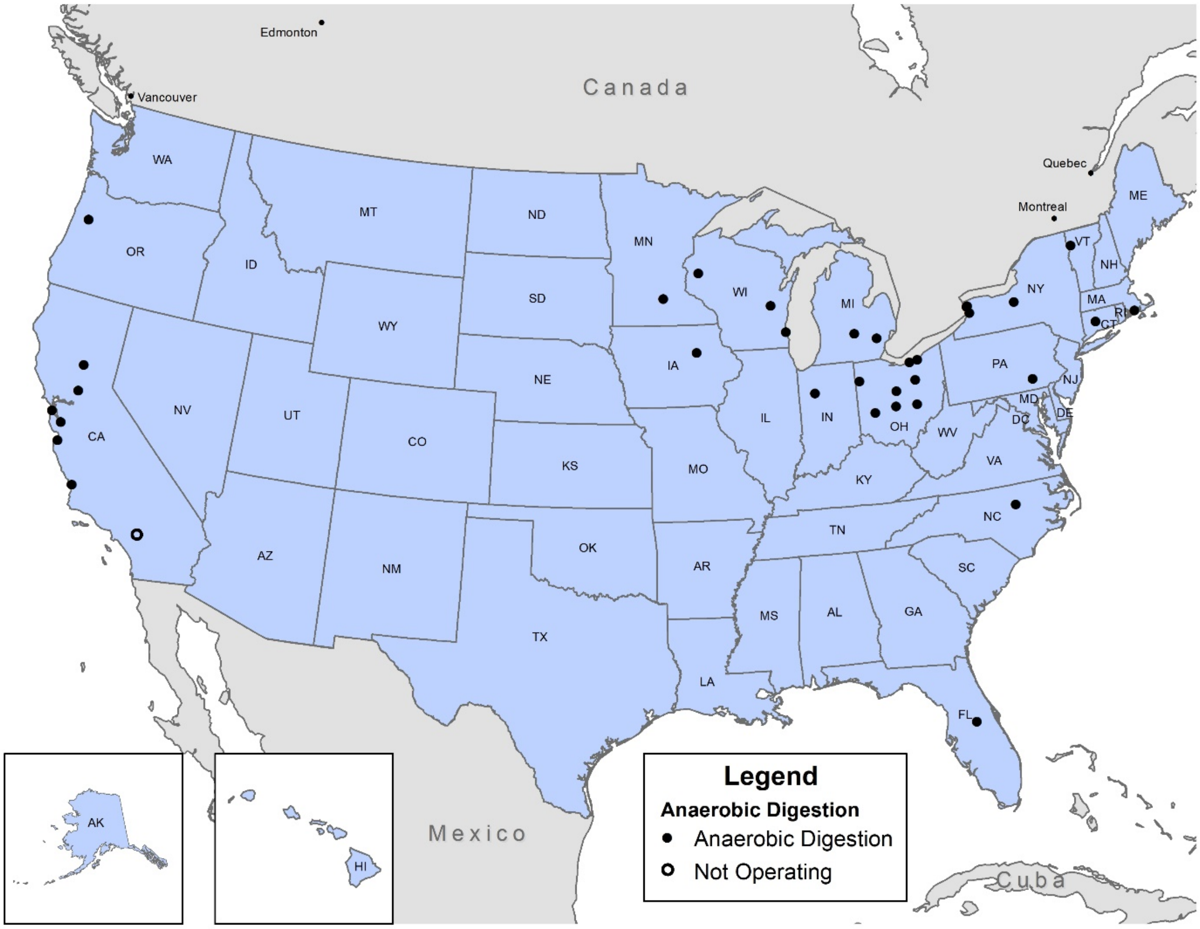


Figure 10. Stand-alone and multi-source anaerobic digestion facilities.

Table 5. Stand-Alone Multi-Source Anaerobic Digestion Facilities

Facility Name	City	State	Feedstock
Operating			
Blue Line Biogenic CNG Facility	South San Francisco	CA	Multi-Source
Buckeye Biogas LLC	Wooster	OH	Multi-Source
Buffalo BioEnergy	West Seneca	NY	Multi-Source
Central Ohio BioEnergy	Columbus	OH	Multi-Source
CH4 Generate Cayuga LLC	Auburn	NY	Multi-Source
City of Waterloo Anaerobic Lagoon	Waterloo	IA	Other
CleanWorld SATS	Sacramento	CA	Multi-Source
Collinwood BioEnergy	Cleveland	OH	Other
CRMC Bioenergy Facility	New Bedford	MA	Other
Dovetail Energy	Fairborn	OH	Multi-Source
Emerald BioEnergy	Cardington	OH	Multi-Source
Forest County Potawatomi Community Digester	Milwaukee	WI	Multi-Source
Full Circle Recycle (Barham Farms)	Zebulon	NC	Multi-Source
Generate Fremont Digester, LLC	Fremont	MI	Multi-Source
Generate Niagara Digester	Wheatfield	NY	Multi-Source
Greenwhey Energy	Turtle Lake	WI	Multi-Source
Harvest Power Orlando	Lake Buena Vista	FL	Multi-Source
Haviland Energy	Haviland	OH	Multi-Source
Hometown BioEnergy	Le Sueur	MN	Multi-Source
Kline's Services	Salunga	PA	Multi-Source
Kompogas SLO LLC	San Luis Obispo	CA	Multi-Source
Magic Hat Resource Recovery Center	South Burlington	VT	Multi-Source
Michigan State Univ. – South Campus AD	Lansing	MI	Multi-Source
Niagara BioEnergy	Wheatfield	NY	Multi-Source
North State Rendering	Oroville	CA	Multi-Source
Quantum Biopower	Southington	CT	Multi-Source
Stahlbush Island Farms	Corvallis	OR	Other
Three Creek BioEnergy, LLC	Sheffield Village	OH	Multi-Source
UW-Oshkosh Urban Dry Digester	Oshkosh	WI	Multi-Source
Waste No Energy, LLC	Monticello	IN	Multi-Source
Zanesville Energy	Zanesville	OH	Multi-Source
Zero Waste Energy - San Jose	San Jose	CA	Multi-Source
Zero Waste Energy - Monterey	Marina	CA	Multi-Source
Not Operating			
Rialto Bioenergy Facility (under construction)	Rialto	CA	Multi-Source

Source: US EPA, 2019

Chapter 6: Life Cycle Environmental Profiles

The US and the international community are focusing increasingly on a life-cycle materials management paradigm that considers the environmental impacts of materials at all life-cycle stages. Recognition is growing that, since traditional environmental policies focus on controlling "end-of-pipe" emissions, they do not provide a means for systematically addressing environmental impacts associated with the movement of materials through the economy.

The LCI data developed in the 2012 report, *State of Practice for Emerging Waste Conversion Technologies* (US EPA, 2012), was based on technology vendor-supplied estimates for operating parameters (e.g., unit of energy output and emissions per unit of feedstock input). In this report, LCI data were collected for conversion technologies by performing a comprehensive literature review of recent papers and reports covering the technologies. The LCI data resulting from this literature were compared to modeled LCI data generated for the alternatives of conventional WTE and landfill using MSW DST.

6.1 LCI Data Review

Life cycle environmental profiles, including energy and resource inputs, emissions, product, and residual outputs were developed for pyrolysis, gasification and AD technologies based on a literature review. The literature review was conducted with peer-reviewed sources available from academic and trade publications and technical reports from government agencies. Data was collected for each source within the scope of the review. These data include authors, year of publication, title of article, journal name, volume and page numbers, web address and access date. The review was conducted using the following keywords independently and in combination:

- life cycle assessment, life cycle inventory, life cycle approach
- municipal solid waste, solid waste, MSW
- waste-to-energy, WTE
- waste conversion
- anaerobic digestion, AD
- pyrolysis
- gasification
- waste
- energy
- technologies
- inventory
- operations
- data

These searches yielded 60 total studies, which were included in the companion literature review Excel tracking template. There were 48 studies that were conducted since 2012. After this initial search effort, the studies were scanned to determine the technologies and feedstocks assessed as well as the geographic location of the study. An evaluation was conducted to generate a short summary and a rating for the relevance of each study relative to the project scope using a low/medium/high scale. Examples of low relevance studies include those that did not evaluate the technologies of concern, provided no inventory data or used data from another source, or explicitly focused on developing countries. Examples of medium relevance studies include those that provide some parameters for the technologies of concern or provide significant data for related technologies which may be useful (e.g., 'combustion' or 'incineration'). A high relevance study is defined as one that provides significant data for the technologies of concern.

Twenty-three studies out of the 60 identified were deemed to be of medium and high relevance. LCI data from these studies was extracted and compiled in a Microsoft Excel workbook. Data compiled were subsequently harmonized in terminology (i.e., labeling of parameters) and normalized converted to common units (e.g., kg, L, MJ) per tonne of feedstock.

In conducting this review and analysis of waste conversion technologies, a number of challenges were encountered pertaining to the ability to collect and validate certain technology and LCI data. Specific limitations include:

- The viability of available information or data could not be independently verified due to the lack of performance data or independent testing or verification. No attempt was made to directly communicate with technology vendors (e.g., by email, telephone or direct contact) but rather data and information were collected from publicly available sources.
- The dynamic nature of waste conversion technologies and markets. Many pyrolysis and gasification facilities are at a pilot or semi-commercial stage. It was found that even facilities that are commercial scale are often operating in more of a demonstration mode.
- The lack of facility-specific information publicly available online, either published by market actors or third parties (e.g., the media, independent evaluations, academic studies). Several companies reviewed did not have their own websites, while others operated websites that appear to be several years out of date.
- LCI data available in the literature was found to be limited for the technologies studied. In several cases, only one data point was found in the literature, which limited the ability to develop robust LCI data ranges. In addition, it was difficult to determine scope and boundaries among sources, thus limiting the ability to make direct comparisons. For example, one source may include resource use and emissions associated with the conversion process as well as syngas cleaning and combustion in a turbine or an internal combustion engine for electricity production. Another source may include only the resource use and emissions associated with the conversion process proper.

6.1.1 Pyrolysis LCI Data

The life cycle assessments[70] (LCAs) of pyrolysis vary between gas production and the generation of other products such as biochar or liquid feedstocks, which can be utilized as fuel or in chemical feedstocks. In some cases, there is not a clear distinction between gasification and pyrolysis. Because pyrolysis is a method of gasification or a process in other approaches to gasification, pyrolysis is sometimes referred to as gasification or in conjunction with gasification within the literature. The LCAs for pyrolysis mainly evaluated MSW, plastics, and dry organics as a feedstock because moisture inhibits the process and demands more energy inputs to the process. Of the seven LCAs identified for pyrolysis shown in **Table 6**, five represent western countries, with two explicitly evaluating US-based systems.

Table 6. Summary of Pyrolysis Life Cycle Inventory Literature Review

Citation	Location	Waste Feedstock	Relevance
Al-Salem et al., 2014	London, England	plastic solid waste, MSW	medium/high
Chakraborty et al., 2013	Delhi, India	MSW	medium

[70] Life cycle assessment combines the life cycle inventory results into impact categories such as cancer and non-cancer impacts, tropospheric ozone, climate change and other impact categories that affect human health and the environment.

Citation	Location	Waste Feedstock	Relevance
Evangelisti et al., 2015	United Kingdom	MSW	medium/high
Ibarrola et al., 2012	United Kingdom	green waste, food waste, wood waste, cardboard, dense refuse-derived fuel	medium
Jones et al., 2014	United States	Wood	medium
Wang et al., 2015	United States	MSW	medium/high
Zaman, 2013	unspecified	MSW	medium

6.1.2 Gasification LCI Data

Gasification is described in multiple sources as an improved method of combustion due to the ability to control certain emissions and is the most represented technology in the scope of this literature review. As mentioned in the previous section, there often is not a clear distinction in the literature between gasification and pyrolysis. There are several technologies that are referred to as gasification, including pyrolysis. The majority of LCAs for gasification evaluated MSW as a feedstock because of the lower sensitivity these technologies have relative to feedstock characteristics. Of the 13 LCAs identified for gasification in **Table 7**, seven represent western countries, with only one explicitly evaluating US-based systems.

Table 7. Summary of Gasification Life Cycle Inventory Literature Review

Citation	Location	Waste Feedstock	Relevance
Arafat et al., 2015	unspecified	food, yard, plastic, paper, wood, textile	medium/high
Arena et al., 2015	Europe	unsorted residual waste	medium/high
Chakraborty et al., 2013	Delhi, India	MSW	medium
Consonni and Viganò, 2012	Unspecified	MSW	medium/high
Del Alamo et al., 2012	unspecified	MSW	medium
Evangelisti et al., 2015	United Kingdom	MSW	medium/high
Ibarrola et al., 2012	United Kingdom	green waste, food waste, wood waste, cardboard, RDF	medium
Ionescu and Rada, 2012	Europe	MSW	medium
Ionescu et al., 2013	Europe	MSW	medium
Kourkumpas et al., 2015	Europe	MSW, RDF	medium
Pressley et al., 2014	United States	RDF, MSW	medium/high
Smith et al., 2015	Unspecified	organic fraction of MSW	medium
Zaman, 2013	Unspecified	MSW	medium

MSW, municipal solid waste; RDF, refuse-derived fuel

6.1.3 Anaerobic Digestion LCI Data

The primary solid waste feedstock considered in LCAs of AD was the organic fraction of MSW or food wastes due in large part to the associated moisture content. Of the studies identified for AD, as shown in **Table 8**, only three represent western countries, with only two explicitly evaluating US-based AD systems. The US-based studies did not include LCI data set but rather data characterizing specific elements of AD such as energy production and greenhouse gas (GHG) emissions that may be used to construct an LCA.

Table 8. Summary of Anaerobic Digestion Life Cycle Inventory Literature Review

Citation	Location	Waste Feedstock	Relevance
Arafat et al., 2015	Unspecified	food, yard, plastic, paper, wood, textile	medium/high
Chakraborty et al., 2013	Delhi, India	MSW	medium
Evangelisti et al., 2014	United Kingdom	organic fraction of MSW	medium/high
Moriarty, 2013	United States	food waste	medium
Smith et al., 2015	Unspecified	organic fraction of MSW	medium
Williams et al., 2016	United States	animal manure, food, leaves, grass	medium/high

6.1.4 Review Papers and Other Relevant Literature

The following studies in **Table 9** were broad in scope and included a variety of technologies and feedstocks for comparison. These studies all rank high in terms of relevance and may provide useful context and parameter ranges for the technologies. The references contained within these studies provide additional data.

Table 9. Summary of Review Articles

Citation	Location	Waste Feedstock	Relevance
Arena, 2012	Unspecified	Various	high
Astrup et al., 2015	Various	Various	high
Kumar and Samadder, 2017	Global	Various	high
Laurent et al., 2014	Europe	Various	medium/high

6.2 LCI Data Compilation

The goal of the LCI data collection effort was to identify the most relevant data pertaining to the conversion of MSW to energy through the utilization of pyrolysis, gasification, and AD in the US. To best achieve that goal, data were prioritized as determined by metrics from the literature review. Only studies with a medium relevance score or greater were considered. In addition, the geographic scope of the studies was considered and were prioritized in the following order: US, other developed nations, unspecified/global, and developing nations. The availability of data for each technology determined whether parameters or single values were used and the uncertainty that may be associated with different variables.

LCI data were extracted from the identified literature sources and compiled in a Microsoft Excel workbook. Data were normalized to a per ton basis to enable comparisons across studies with differing functional units. Where multiple data points existed for a specific input or output, a range of data values were developed. After all data were recorded, average values as well as a range of values were developed for the primary input and output flows. Resulting data were reviewed to assess if any recorded data points were outliers and should be removed.

6.3 LCI Data Coverage and Gaps

Table 10 presents a cursory overview of the LCI data available within the studies that received 'medium' or greater relevance scores. Overall, the data available from the literature were found to be limited in providing robust sets of LCI data for examination and analysis of waste conversion technologies. In many instances, only one data source/point was found for an inventory inflow/outflow category.

The most complete coverage is for the gasification technology, which has the most representation within the literature. Pyrolysis and AD have less coverage but a few key papers (Arena et al., 2015; Astrup et al., 2015; Evangelisti et al., 2015; Wang et al., 2015; Williams et al., 2016) provide comprehensive data that spans the areas of interest for the data collection effort for the targeted technology. Data specific to AD technology accepting food waste and other MSW-based organics was found to be particularly limited. Some of the fields in Table 8 remain empty where the data are not reported using the same classifications or those categories are not associated with the technology modeled within the studies.

Table 10. Inventory Data within the Literature

Inputs and Outputs			Pyrolysis	Gasification	Anaerobic Digestion
Inputs	Power Consumption/ parasitic load		Al-Salem et al., 2014 Jones et al., 2014 Wang et al., 2015	Ionescu and Rada, 2012	Evangelisti et al., 2014
	AD Process Characteristics	Total Solids		Pressley et al., 2014	Moriarty, 2013 Williams et al., 2016
		Volatile Solids		Pressley et al., 2014	Moriarty, 2013 Williams, 2016
		Biodegradable Volatile Solids			Moriarty, 2013 Williams, 2016
		Conversion Efficiency waste to methane			Kumar and Samadder, 2017 Moriarty, 2013 Williams et al., 2016
		Conversion Efficiency methane to electricity			Kumar and Samadder, 2017 Moriarty, 2013 Smith et al., 2015 Williams et al., 2016
	Other inputs	Water	Al-Salem et al., 2014 Evangelisti et al., 2015 (SI)	Astrup et al., 2015 (SI) Evangelisti et al., 2015 (SI)	

Inputs and Outputs			Pyrolysis	Gasification	Anaerobic Digestion
			Jones et al., 2014 Wang et al., 2015		
		Oxygen			
		Catalysts and chemicals	Al-Salem et al., 2014	Arena et al., 2015 Astrup et al., 2015 (SI)	
		Diesel for preprocessing	Jones et al., 2014 Wang et al., 2015		
		Caustic for gas cleaning and cooling		Astrup et al., 2015 (SI)	
		Activated Carbon for gas cleaning and cooling		Arena et al., 2015 Astrup et al., 2015 (SI)	
		Feldspar for gas cleaning and cooling	Evangelisti et al., 2015 (SI)	Evangelisti et al., 2015 (SI)	
	Supplemental fuel use	Natural Gas		Astrup et al., 2015 (SI)	
Outputs	Energy product	Electricity		Arena, 2012 Arena et al., 2015 Chakraborty et al., 2013 Consonni and Viganò, 2012 Ionescu and Rada, 2012	Chakraborty et al., 2013 Evangelisti et al., 2014 Moriarty, 2013 Smith et al., 2015
		Syngas	Al-Salem et al., 2014	Del Alamo et al., 2012 Arena, 2012 Consonni and Viganò, 2012 Ionescu and Rada, 2012 Pressley et al., 2014	Moriarty, 2013
		Crude oil	Wang et al. 2015		
		Light fraction (liquid)	Al-Salem et al., 2014		
		Gas fraction			
		Gasoline	Wang et al. 2015	Smith et al., 2015	
		Diesel	Wang et al. 2015		
	Material byproducts	Residual gas			
		Sulfur			
		Salt	Al-Salem et al., 2014		

Inputs and Outputs			Pyrolysis	Gasification	Anaerobic Digestion
		Slag			
	Residuals	Char	Wang et al. 2015		
		Slag		Arena et al., 2015 Consonni and Viganò, 2012	
		Spent catalysts and chemicals			
		Solid residues	Al-Salem et al., 2014 Evangelisti et al., 2015	Arena, 2012 Evangelisti et al., 2015	
		Inorganic sludge		Arena et al., 2015	
		Nonhazardous solid waste	Evangelisti et al., 2015	Del Alamo et al., 2012 Evangelisti et al., 2015	
	Water losses		Jones et al., 2014		
Air Emissions Data		PM	Evangelisti et al., 2015 Evangelisti et al., 2015 (SI) Wang et al. 2015	Arena, 2012 Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 Evangelisti et al., 2015 (SI) Smith et al., 2015 Zaman, 2013	Smith et al., 2015 Williams et al., 2016
		PM10	Wang et al. 2015		
		Biogenic Carbon Dioxide	Evangelisti et al., 2015 (SI) Jones et al., 2014 Wang et al. 2015	Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 (SI) Kourkoumpas, 2015 Smith et al., 2015 Zaman, 2013	Evangelisti et al., 2014 Smith et al., 2015 Williams et al., 2016
		Fossil Carbon Dioxide	Jones et al., 2014	Arena et al., 2015 Astrup et al., 2015 (SI)	
		Methane	Jones et al., 2014 Wang et al. 2015	Astrup et al., 2015 (SI)	Evangelisti et al., 2014 Smith et al., 2015 Williams et al., 2016
		Hydrochloric Acid	Evangelisti et al., 2015	Arena, 2012 Evangelisti et al., 2015 Zaman, 2013	

Inputs and Outputs		Pyrolysis	Gasification	Anaerobic Digestion
	Sulfur Dioxide	Evangelisti et al., 2015 Evangelisti et al., 2015 (SI)	Arena, 2012 Arena et al., 2015 Evangelisti et al., 2015 Evangelisti et al., 2015 (SI) Smith et al., 2015 Zaman, 2013	Smith et al., 2015 Williams et al., 2016
	Sulfur Oxide		Arena, 2012 Astrup et al., 2015 (SI)	Williams et al., 2016
	Mercury	Evangelisti et al., 2015 (SI)	Arena, 2012 Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 (SI) Zaman, 2013	
	Cadmium		Arena et al., 2015 Astrup et al., 2015 (SI) Zaman, 2013	
	Hydrocarbons			
	Nitrous Oxide	Evangelisti et al., 2015 (SI)	Arena, 2012 Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 (SI)	Williams et al. , 2016
	NOx expressed as NO_2	Evangelisti et al., 2015 Evangelisti et al., 2015 (SI)	Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 Evangelisti et al., 2015 (SI) Smith et al., 2015	Evangelisti et al., 2014 Smith et al., 2015 Williams et al., 2016
	Carbon Monoxide	Evangelisti et al., 2015 Evangelisti et al., 2015 (SI) Jones et al., 2014 Wang et al. 2015	Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 Evangelisti et al., 2015 (SI) Smith et al., 2015 Zaman, 2013	Evangelisti et al., 2014 Smith et al., 2015 Williams et al., 2016
	Lead	Evangelisti et al., 2015 (SI)	Arena et al., 2015 Astrup et al., 2015 (SI) Evangelisti et al., 2015 (SI)	

Inputs and Outputs		Pyrolysis	Gasification	Anaerobic Digestion
	VOC	Evangelisti et al., 2015 (SI)	Arena et al., 2015 Evangelisti et al., 2015 (SI) Smith et al., 2015 Zaman, 2013	Evangelisti et al., 2014 Smith et al., 2015 Williams et al., 2016
	Hazardous Air Pollutant	Evangelisti et al., 2015 (SI)	Evangelisti et al., 2015 (SI)	
	Acetaldehyde			
	Total non-methane organic carbon	Wang et al. 2015		
	Dioxins and Furans		Arena, 2012 Arena et al., 2015 Astrup et al., 2015 (SI) Zaman, 2013	
Cost Data	Cost per ton of design capacity	Jones et al., 2014 Kumar and Samadder, 2017	Chakraborty, 2013 Kumar and Samadder, 2017 Smith et al., 2015	Chakraborty et al., 2013 Kumar and Samadder, 2017 Moriarty, 2013 Smith et al., 2015 Williams et al., 2016

AD, anaerobic digestion; PM, particulate matter; VOC, volatile organic compound

6.4 LCI Comparison to Conventional WTE and Landfill

In this section, select LCI data resulting from the literature review for pyrolysis and gasification technologies are compared to modeled LCI data ranges for AD, conventional WTE and landfill developed using the MSW DST. Since complete LCI data specific to the MSW-based feedstock AD were not available from the literature, the AD model[71] developed for the Solid Waste Optimization Life-cycle Framework, or SWOLF (which is being incorporated into a forthcoming new version of the MSW DST) was used to provide LCI data for AD. The ranges for AD represent average values for food and non-food (e.g., yard wastes) organic waste constituents. The values for WTE and landfill with gas collection and energy recovery were developed by modeling typical MSW feedstocks accepted by conversion technologies including:

- MSW
- plastics
- food/organics

The MSW DST was developed to aid communities and solid waste planning in evaluating the cost and life-cycle environmental impacts for different MSW management technologies and strategies. Default national average settings were used for AD, WTE, and landfill design and operational parameters. For landfill, gas management with energy recovery (via electricity generation) was modeled. The national average grid mix for electricity production was used to calculate emissions associated with electricity

[71]Model documentation available at: http://www4.ncsu.edu/~jwlevis/AD.pdf

consumption and emission offsets in the case of AD, WTE and landfill. An uncertainty factor of 20 percent was applied to the average LCI results to develop ranges for AD, WTE, and landfill.

As highlighted in the previous sections (6.1—6.3), the data available from the literature were found to be limited in terms of providing robust sets of LCI data for analysis and comparison to conventional WTE and landfill disposal. Therefore, ***making direct LCI comparisons between conversion technologies and between conversion technologies and conventional technologies is challenging.*** Findings from the literature review point to common challenges:

- Different MSW feedstocks are accepted by different technologies. While conventional WTE and landfill can accept bulk MSW as-is, conversion technologies often are tailored to specific fractions of MSW. Pyrolysis typically focuses on non-recycled plastics but also can include facilities designed for conversion of biomass feedstock (typically non-MSW agriculture and forestry residues). AD can be designed to accept food waste or mixed organics from MSW. Gasification may accept bulk MSW or fractions thereof (e.g., MRF residuals) but will require robust preprocessing to remove unwanted materials (e.g., glass, fines).
- A variety of end-products can be produced by conversion technologies. Gasification produces a syngas product that may be used directly to generate electricity or transformed to a liquid fuel. Pyrolysis produces a synthetic petroleum product that may be refined to a liquid fuel or into chemical commodities. AD produces biogas and a digestate product that may be used as compost. These differing products were normalized for comparative purposes by reporting in terms of heating value (MJ / [mass unit]).
- LCA literature for conversion technologies are not always clear about system boundaries. Life cycle burdens associated with waste collection transport, preprocessing of feedstock, post-processing of product (e.g., syngas cleaning), and use (e.g., combustion) are often difficult to discern in the data and may or may not be included altogether. Unless otherwise noted, the LCI results assume collection is not part of the data boundaries.
- LCI data from the literature represent different time spans and technology development cycles. Waste conversion is a developing technology. Vendors are continually refining process designs to obtain greater efficiencies and more stable operations. Thus, the LCI data available in the literature represents a wide range of technology design and various stages of technology development and refinement. This can cause wide-ranging data and potential outliers. As an example, one source for gasification included a novel syngas-cleaning technology that consumes significantly greater amounts of water than other sources and may be considered an outlier.

The following sections contain LCI estimates for energy consumption, water consumption, carbon emissions, and solid residuals. LCI results are presented on a per tonne of feedstock. Additional LCI data for pyrolysis and gasification technologies are provided in Attachments D and E, respectively.

6.4.1 Energy Consumption and Production

The primary benefit touted for waste conversion technologies is their ability to generate energy products from waste that otherwise would be disposed of in a landfill. However, they do not have the performance data or proven ability to recover energy, metals, and other resources as a WTE facility. The residuals from pyrolysis and gasification if managed by WTE would recover additional energy, which would not occur in a landfill. Currently, most residuals are landfilled. Thus, the potential ability of conversion technologies to achieve levels of energy recovery greater than conventional options is important to consider. For conversion technologies, energy is consumed to power the conversion process, facility equipment (e.g., rolling stock, feedstock preprocessing, air pollution control) and transport and disposal of residuals in a landfill. Energy consumption results include data for electrical and fossil fuel energy consumption. The net energy consumption results shown in Figures 11a through 11c highlight that conversion technologies have the "potential" of energy recovery. However, conversion technologies do not have the performance history that WTE facilities have in the US, Europe, and Japan. Those WTE facilities which have 24/7 continuous monitoring data demonstrate that emissions are even lower than regulatory standards. In considering waste conversion technology, the net energy production must include both preprocessing and post-processing requirements for that technology.

Note that for WTE of MSW feedstock, as shown in figure 8a, ferrous metal recovery from combustion ash is also included which provides an additional energy offset benefit per the consumption of energy otherwise needed to produce virgin ferrous metal. In addition, differences in MSW feedstock composition (and energy value) will significantly impact energy recovery. For gasification, it was not always possible to determine the composition of MSW that was assumed in the literature sources whereas for WTE and landfill a US average composition was modeled.

For plastics feedstock, as shown in figure 11b, it is surprising that the net energy results exhibit WTE as performing better on an energy basis than pyrolysis. These results are difficult to reconcile as one would expect gasification to be a more efficient process than a mass-burn WTE plant and yield better energy returns. One possible explanation could be due to differences in the assumed MSW feedstock composition and subsequent energy value as previously stated. Another factor may be the type of energy that is assumed to be offset per each technology (i.e., electricity for WTE and fuel oil for pyrolysis). These results may also be due to greater economies of scale for WTE, which are typically larger-scale facilities with greater capacities and thus a lower parasitic power load relative to smaller-scale pyrolysis facilities.

For food waste, as shown in figure 11c, net energy is more comparable among the options analyzed. It is interesting to note that WTE is on par or a slightly better on an energy basis than AD. This may be due to a more complete energy value of the food being recovered in WTE than AD, where the remaining carbon in AD goes to digestate.

Figure 11a. Net energy production for MSW feedstock.

(Note: WTE includes energy offsets associated with metals recovery and recycling.)

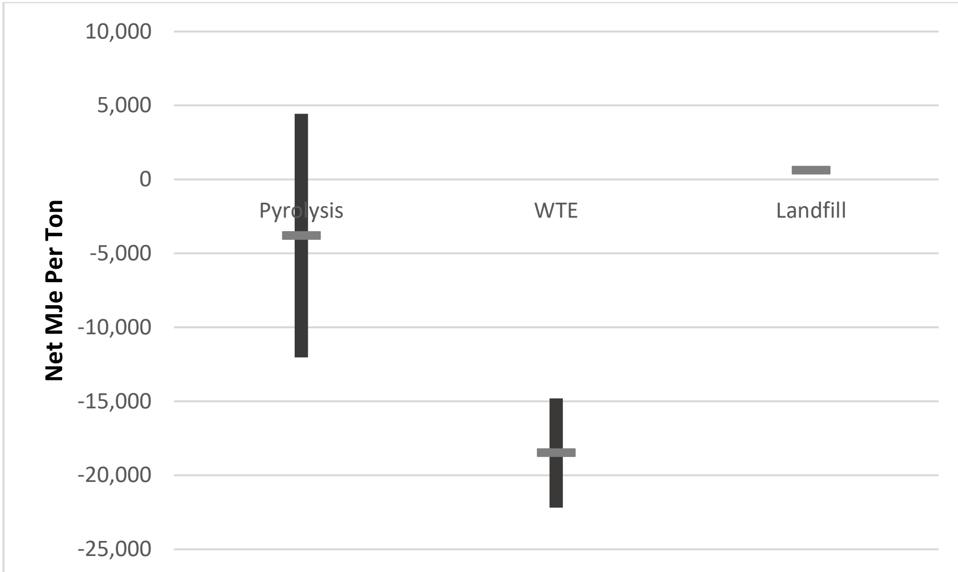


Figure 11b. Net energy production for plastic waste feedstock.

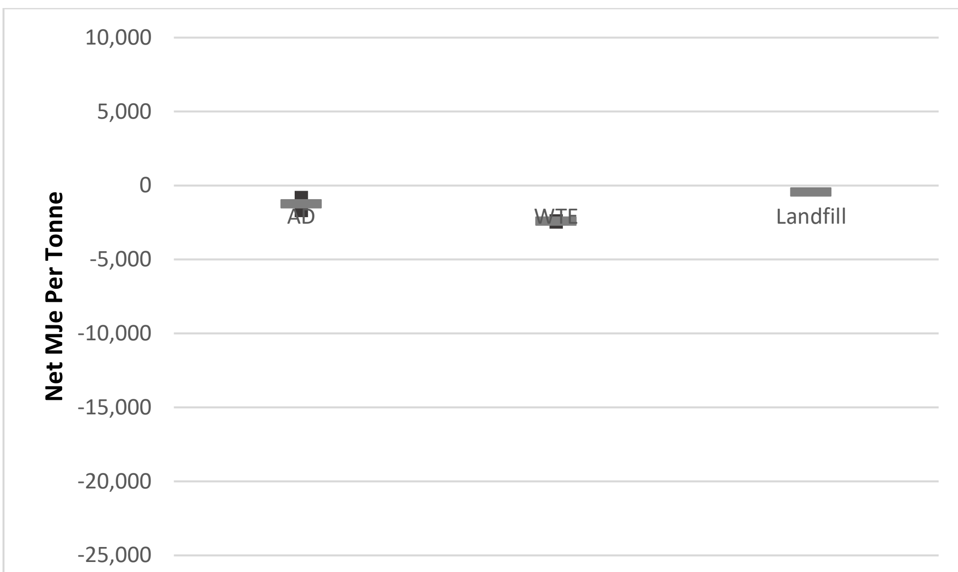


Figure 11c. Net energy production for food/organic waste feedstock.

6.4.2 Water Consumption

Water is typically not a process input for conversion technology facilities, except for AD when there is not enough moisture in the feedstock. However, water can be consumed as part of feedstock preprocessing (e.g., washing of plastics) as well as gas or fuel cooling/cleaning and air pollution control. **Figure 12** shows water consumption estimates available from the literature for conversion and conventional waste treatment and disposal technology. A review of the gasification LCI data from the literature revealed that one specific technology represented used a syngas cleaning process that appears to consume large amounts of water. Including this large water consumption value pulls up the average from approximate 9,000 kg of water per tonne to almost 70,000 kg of water per tonne. While this one data point was an outlier and was excluded, it does highlight the need to carefully review data to determine whether it captures all aspects of a conversion process. In this case, cleaning of the resulting syngas to meet market requirements is the culprit. For other gasification technologies, the syngas cleaning stage does not consume such large amounts of water or possibly is not included at all.

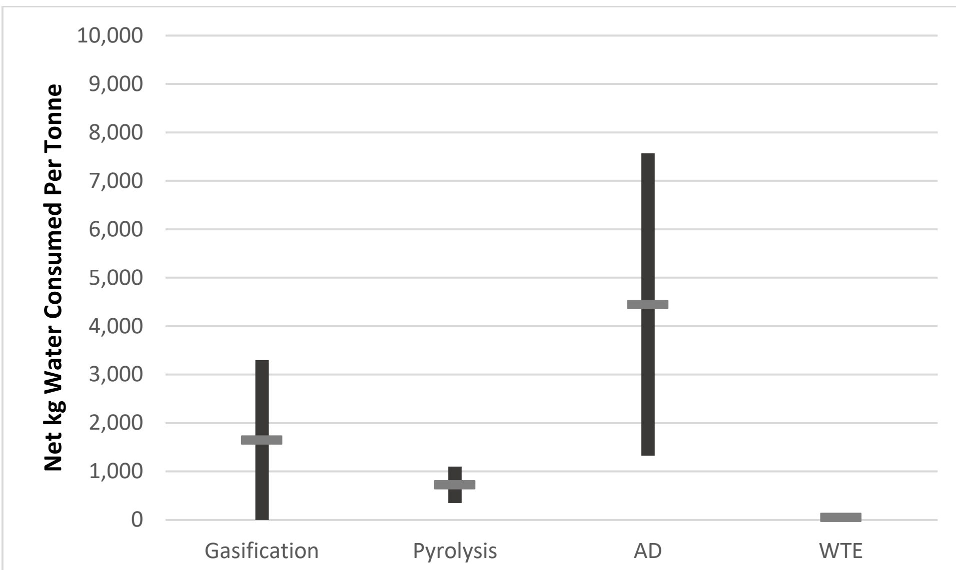


Figure 12. Net average life cycle water consumption.

6.4.3 Carbon Emissions

Carbon emissions contribute to the greenhouse effect; thus, these emissions can lead to climate change and its associated impacts. Carbon emissions can result from the combustion of fossil fuels and the biodegradation of organic materials (e.g., methane gas from landfills). Offsets of carbon emissions can result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills. Carbon emissions are presented in units of kilograms of carbon dioxide equivalent, derived using global warming potentials (GWP) as follows:

$$kg\ CO_2e = (Fossil\ CO_2 * CO_2GWP) + (CH_4 * CH_4GWP)$$

Where:
CO_2 GWP=1
CH_4 GWP=25

Reductions and offsets of carbon emissions are directly related to the following aspects:

- Electrical energy production offsets carbon emissions from the generation of electrical energy using fossil fuels in the utility sector.
- Materials recovery and recycling offsets carbon emissions by avoiding the consumption of energy that otherwise would be used in materials production processes.

Carbon emissions are generally minimal for the conversion processes proper as the thermal, chemical and biological reactions takes place in sealed reactors/vessels. Carbon emissions, namely CO_2, will result from any on-site combustion of fossil fuel to power vehicles and equipment and possibly to provide additional heat to the process. For pyrolysis and gasification, the main source of carbon emissions will be the end-use combustion of the syngas or synfuel product. For AD and landfill, combustion of the recovered biogas product will produce biogenic CO_2 emissions, which is typically considered to be carbon neutral. Likewise, direct combustion of organics via WTE will produce biogenic CO_2 emissions, which are not included in the CO_2e calculations.

Figures 13a through 13c show the net total carbon equivalent emissions for conversion technologies as compared to the modeled carbon equivalent emissions for WTE and landfill. Since CO_2 and methane data were available from the literature, these data were used to normalize carbon equivalent emissions.

For MSW feedstock, as shown in figure 13a, landfills produce the highest carbon emissions, as expected. Somewhat unexpected is that gasification exhibits higher carbon emissions than WTE. However, as shown in figure 11a, WTE exhibited a better energy profile and carbon emissions will be closely tied to energy. In addition, there are likely differences in carbon intensities of electricity grids being displaced per the data sources for gasification that were not possible to normalize to the US average grid as used for WTE (as well as for AD and landfill). In addition, it is not always possible to determine the composition of MSW feedstock that was assumed in the literature sources for gasification, which will impact carbon emission results. For AD, WTE and landfill the US average MSW composition is assumed.

Carbon emission results for plastics, as shown in figure 13b, exhibit net positive carbon emissions for WTE and conversion technologies. Again, this is due to the direct combustion (via WTE) of plastics or the combustion of fuel products (via gasification and pyrolysis) made from plastics producing fossil CO_2 emissions. For food waste, as shown in figure 13c, it is interesting to note that AD exhibits higher carbon emissions that WTE. This result is primarily due to the accounting of methane leakage for AD. The combustion of food/organic feedstock in WTE and the combustion of biogas produced from AD will result in biogenic carbon emissions that are not included in the carbon equivalency calculation.

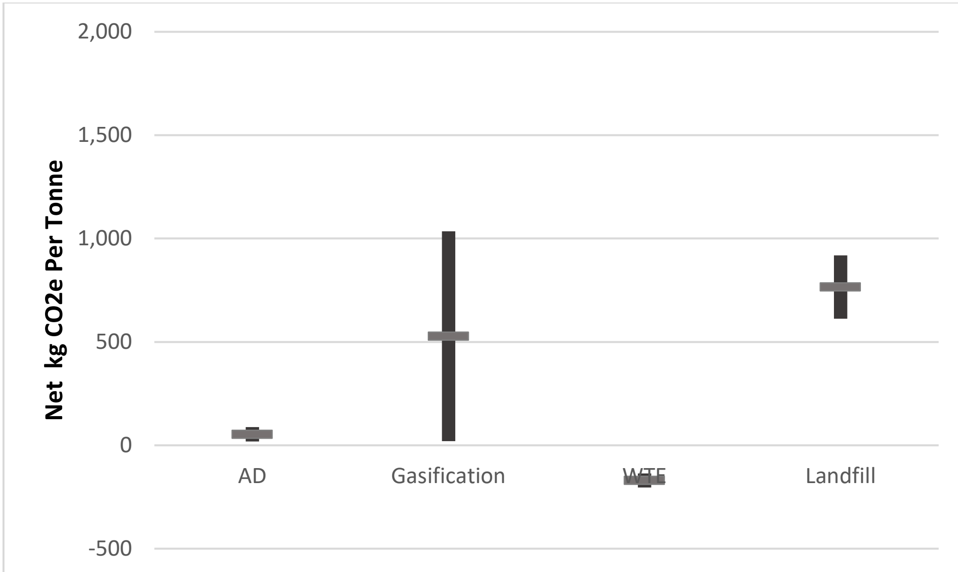


Figure 13a. Net carbon dioxide equivalent emissions for MSW feedstock.

(Normalized for reported CO_2 and CH_4 emission using a GWP of 1 for fossil CO_2 and 25 for CH_4; WTE includes carbon offsets associated with metals recovery and recycling)

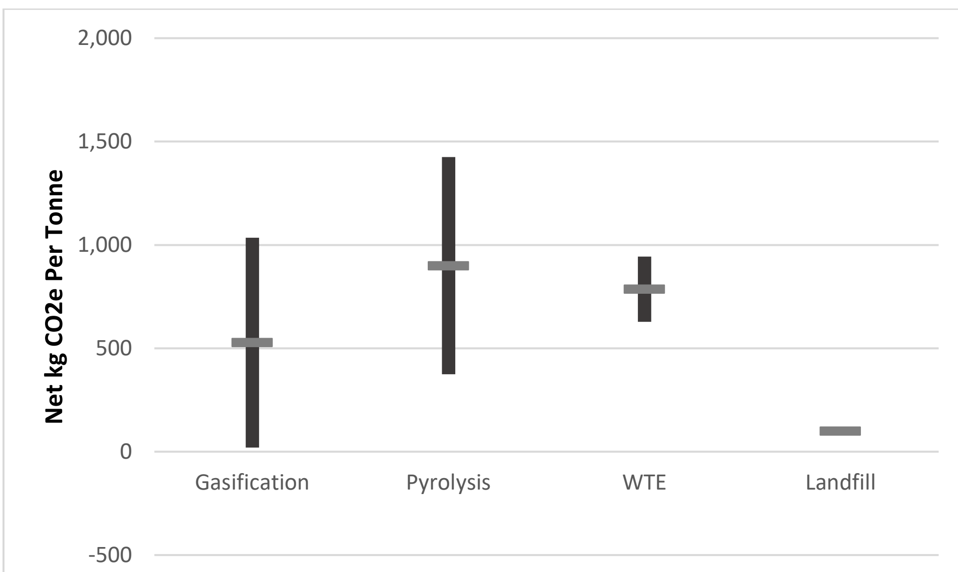


Figure 13b. Net Carbon Dioxide Equivalent Emissions for Plastic Waste Feedstock

(Normalized for reported CO_2 and CH_4 emission using a GWP of 1 for fossil CO_2 and 25 for CH_4)

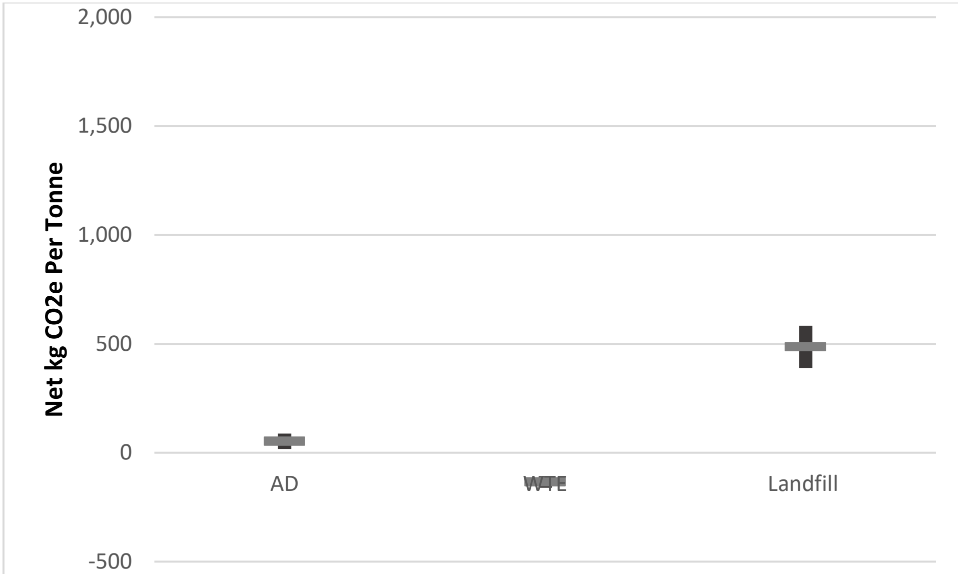


Figure 13c. Net Carbon Dioxide Equivalent Emissions for Food/Organic Feedstock
(Normalized for reported CO_2 and CH_4 emission using a GWP of 1 for fossil CO_2 and 25 for CH_4)

6.4.4 Solid Residuals

All conversion technologies will produce residuals that will require disposal in a landfill or sent to a WTE facility for further energy and metal recovery. Conversion technology by-products may also require treatment or disposal if a viable end-use or market cannot be found. **Figure 14** shows literature estimates for solid residuals (not including by-products) for conversion technologies as compared to the modeled solid residuals per conventional WTE and landfill disposal. For conversion technologies, the amount of solid residual generated will be dictated by the feedstock composition and the level of acceptable contamination by specific conversion technology. In general, it could be expected that mixed feedstock (e.g., MSW, MRF residuals) will generate greater amounts solid residuals than a source segregated feedstock (e.g., plastics, food waste). For WTE, the primary solid residual is combustion ash, which is also dependent on the composition of the feedstock. No solid residuals are expected for landfills as they are considered a final destination for materials

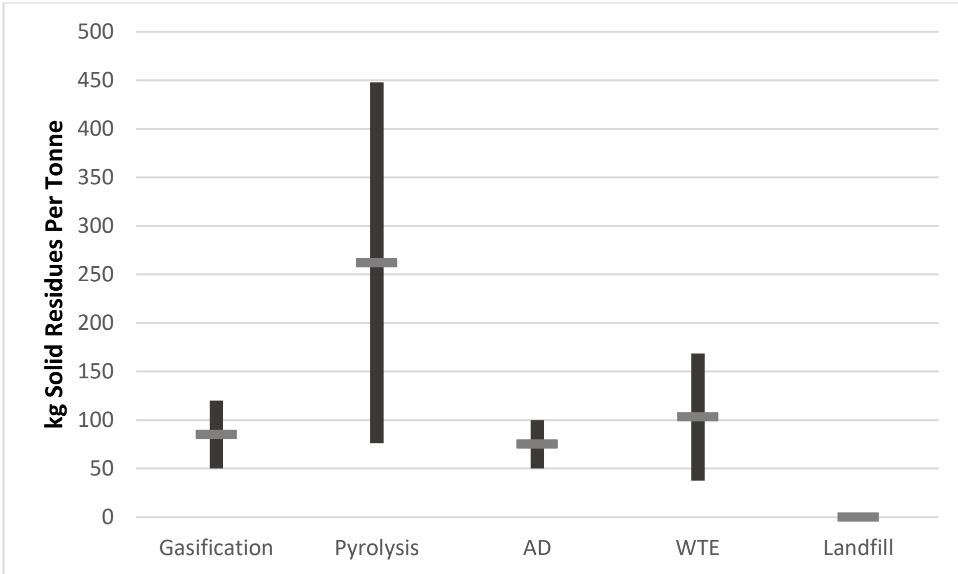


Figure 14. Net average life cycle solid residues generated.

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Chapter 7: Findings and Observations

To solve some of the waste sector's most pressing challenges and exploit some of its newest opportunities, waste conversion technologies will continue to draw interest and investment. As these conversion technologies are being promoted and distributed by private sector stakeholders across the US, communities will need to better understand not only the novelty and potential of each technology type, but also the potential technical, environmental, economic and social impacts of the technologies in their local context.

Waste conversion technologies can provide technically feasible alternatives to conventional WTE and landfill disposal for managing MSW, particularly for non-recyclable MSW fractions that otherwise would be landfilled. Through this study, approximately 10 MSW gasification and pyrolysis technology projects were identified in the US (and Canada). The study identified 2 operating gasification and 4 operating pyrolysis facilities as of September 2019 dedicated to accepting MSW-based feedstock. In contrast, AD systems have grown rapidly since 2012 with more than 25 facilities in the US that process wasted food and other organic fractions of MSW.

One of the major goals of this research is to develop a Decision Makers Guide for Assessing Municipal Solid Waste Energy Recovery Technologies. The guide is a summary of information contained in the report and is provided as Attachment F. Visuals are provided to illustrate the different options for the different feedstocks in municipal solid waste. Those working with island and tribal communities - as well as other communities, may want to use Appendix F as a guide in helping support the unique needs of island and tribal communities.

7.1 Advantages and Disadvantages of Conversion Technologies

There are only a few commercial waste conversion facilities accepting MSW feedstock and operating at large scales. This has created concerns about the conversion technologies being feasible to build and operate and therefore conventional WTE and landfill disposal may be considered lower-risk options. Conversely, stand-alone AD systems and those co-digesting have grown rapidly in recent years due to a heightened focus on diverting organic fractions of MSW (e.g., food waste) from being disposed in landfills.

An often-cited advantage of conversion technologies as compared to WTE or landfill is their potential to produce a wide variety of products. Syngas from gasification gas can be used on-site to generate electricity or it has the potential to be further refined to produce a variety of chemicals, including methanol, ethanol, and liquid fuels. Syncrude from pyrolysis can produce high-value products, including naphtha, kerosene, and gas-oil from polyolefin feedstocks. However, such variety in gasification and pyrolysis has yet to be demonstrated. Biogas from AD systems can be used on-site to generate electricity, used directly, or can be further refined to produce compressed biogas or liquefied biogas products.

A key disadvantage of the conversion technology as compared to conventional WTE and landfill disposal is the need for consistent and quality feedstock for the process to work effectively. Unlike WTE and landfill where bulk MSW feedstock is readily accepted, the feedstock supply, preprocessing, and handling can represent challenges that can have significant impacts on the performance of the conversion technology. Other key disadvantages cited in the literature include difficulties encountered scaling up facilities from demonstration to commercial scale and reliable specifications of the energy product that is generated from the conversion technology. These specifications are dependent on the types and mixtures of feedstock used.

Conversion technologies will not eliminate the need for landfill disposal. Compared to WTE and landfill facilities that are often designed to accept thousands of tonnes per day of waste, conversion technologies are comparatively small in capacity at typically 50 to 300 tonnes per day and are designed around accepting preprocessed MSW (rather than bulk MSW). In addition, the conversion technologies have residual waste streams that can include non-processible feedstocks and non-reusable process residuals (e.g., char). Feedstocks can also require disposal when the conversion technology facility is down for scheduled and unscheduled maintenance, which could be 10-15% of its annual availability (or 36-55 days per year).

7.2 Life Cycle Environmental Performance

Conversion technologies can provide alternatives for managing MSW as compared to conventional WTE and landfill gas to energy projects. From a life cycle environmental perspective, readily available and objective data and information about the performance of conversion technologies is limited due to less operational history and experience. This lack of operational data and experience makes it difficult to compare conversion technologies to each other and to the conventional options.

Findings from the literature review show common challenges in applying life cycle data, including:

- different MSW feedstocks accepted, by the different technologies and process designs, limit the ability to directly compare life cycle results;
- the wide variety of end-products produced by conversion technologies create wide-ranging estimates of life cycle offsets;
- system boundaries not consistently applied among life cycle studies found in the literature, particularly with regard to the inclusion or exclusion of pre- and post-processing activities; and
- available life cycle data from the literature represent different time spans and at different points in technology development cycles, which can lead to wide-ranging technology performance estimates.

The review and analysis of the LCI data from the literature finds that MSW conversion technologies appear to offer net energy production benefits. However, energy production for conversion technologies will vary significantly based on the exact feedstock used, process efficiency, and any requirements for preprocessing of feedstock or post processing of product streams. Conversion technologies may have a slight theoretical advantage over conventional WTE and landfill gas-to-energy operations, in that the energy conversion efficiency may be better and there is greater flexibility in tailoring end products to meet market demands.

Both conversion technologies and conventional WTE and landfill options, generate gaseous, liquid, and solid emissions that will require treatment or disposal. The literature review did not address hazardous air pollutants, which can be present in gaseous emissions when materials are combusted or converted. For carbon emissions, the literature data available show that pyrolysis and gasification technologies can result in carbon equivalent emissions comparable to either conventional WTE or landfill disposal. This is due to the carbon emissions associated with the combustion of the syngas or synfuel product which is considered fossil energy. For AD systems, the resulting biogas product is considered biogenic energy and shows the lowest carbon equivalent emissions of the options studied.

All conversion technologies will produce residual solid waste streams that will require additional treatment (e.g., via WTE) or disposal in a landfill. Conversion technology by-products may also require treatment or disposal if a viable end-use or market cannot be found. The data available from the literature review show that conversion technologies produce as much or higher amounts of residuals than conventional WTE. The exact amounts of solid residuals generated will be dictated by the feedstock composition and the level of acceptable contamination of the feedstock for the specific conversion technology. In general, it could be expected that an unprocessed mixed feedstock will generate greater amounts of solid residuals than a source segregated feedstock (e.g., plastics, food waste).

7.3 Risk Profiles for Conversion and Conventional Technologies

Waste conversion technologies differ in risk profiles based on the successful deployment of the technology. As we have stated, feedstock availability, economics, and other factors can lead to low probability of a successful technology deployment. Also, the price of landfilling waste remains the lowest cost which might be different if environmental externalities are considered. Specially, some technologies have been proven on a commercial scale while others are still in bench scale or small-scale development and testing stages. Risk profiles[72] for the conversion technologies and conventional MSW management technologies presented in this report are provided in the table below:

Technology	Status	Risk Profile[73]
Anaerobic Digestion	Proven technology; limited US commercial experience with MSW	Moderate to Low
Composting	Proven commercial technology	Low
Landfill	Proven commercial technology	Low
Gasification / Pyrolysis	No operating experience with large-scale operations in the US; Past failures	High
RDF Processing and Combustion	Proven commercial technology; limited US commercial experience	Moderate to Low
WTE Combustion	Proven commercial technology	Low

7.3.1 Economics

Cost estimates for conversion technologies are variable and uncertain due to limited data for commercial scale operating facilities and the high variability in capital and operating costs dependent on location. Capital costs include the purchase of land, construction, equipment, and management costs. Operating costs typically include all facility costs related to MSW feedstock preprocessing, conversion (pyrolysis, gasification, AD), post-processing of product (e.g., syngas cleaning), energy product combustion and electricity generation, and regular maintenance and repair activities.

Revenue sources for conversion technologies can include energy product sales, tipping fees, and material by-product sales. Similar to costs, specific data are limited and highly uncertain as they are highly dependent on the quality of the products and local markets. Renewable energy or tax credits may also be a source of revenue for conversion technologies if they meet certain requirements in GHG emissions.

7.3.2 Siting

Many factors including environmental impacts, economic incentives, feedstock availability, product off-take agreements, and permitting requirements go into facility siting decisions. Consideration of the surrounding community and potential health impacts are also critical factors. Businesses and local agencies that take the time to meaningfully engage communities surrounding proposed facilities and consider the potential burden to vulnerable communities typically have a more efficient permitting process.

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[72] Adapted from Gershman, Brickner & Bratton, Inc. Presentation for Arizona Tribal Energy Association on Waste to Energy Technologies. January 2018

[73] This is not referring to risk to human health and the environment. This is communicating the level of risk in the successful technology development.

EPA's environmental justice mapping and screening tool called EJSCREEN is based on nationally consistent data that combines environmental indicators in maps and reports.[74] EPA used EJSCREEN to evaluate the siting of conversion technology and conventional WTE facilities. For this analysis, 111 facilities (currently operating and under construction) were mapped and then evaluated by the income levels of the communities within one mile of each facility. Low-income is defined as the number or percent of a Census block group's population in households where the household income is less than or equal to twice the federal poverty level. Low-income communities were identified as those with a low-income population that ranks in the 80th percentile or higher for the state percentile ranking for low-income. Low-income communities are more likely to experience disproportionate environmental harms and risks as a result of greater vulnerability to environmental hazards.

- Of 111 facilities mapped, 29 are in low-income communities. See **Figure 15** for the distribution of facilities by technology type based on population and state percentile ranking for low income.
- By technology type, RDF facilities had the highest percent, at 64%, of facilities located within one mile of low-income communities, followed by pyrolysis (43%) and mass burn (24%).
- While newer technologies (AD, gasification, and pyrolysis) tend to be in areas with lower population densities, older technologies such as mass burn are surround by denser populations with the potential to impact greater numbers of low-income individuals.

Technology Type	Total Number of Facilities Mapped	Above the 80th percentile based on state percentile ranking for low income	
		Total #	Percent
RDF	11	7	64%
Pyrolysis	7	3	43%
Mass Burn	62	15	24%
AD	27	4	15%
Gasification	4	0	0%

AD, anaerobic digestion; RDF, refuse-derived fuel

[74] US EPA EJSCREEN: Environmental Justice Screening and Mapping Tool. www.epa.gov/ejscreen

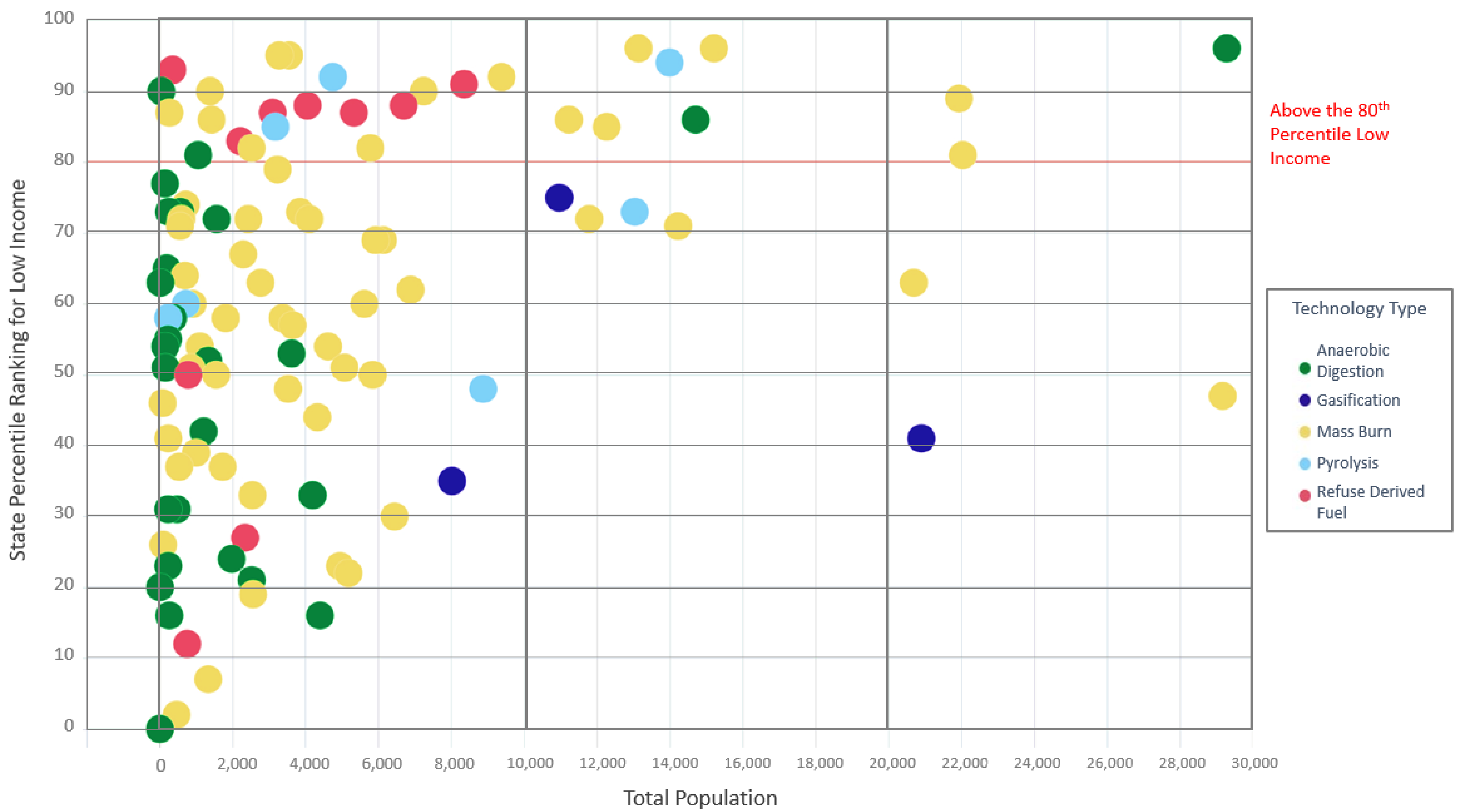

Figure 15. Total population and percentile low-income within one mile of each facility.

Using EPA's EJSCREEN tool, 111 facilities were mapped to assess demographic information on total population and income at a Census block group level within one mile of each facility. Based on the state percentile ranking for income, 29 facilities are surrounded by communities considered to be low-income because they were at or above the 80th percentile.

7.3.3 Permitting Requirements

State regulations and permitting requirements for conventional MSW adopt standards equal to or more stringent than federal law, including the Resource Conservation and Recovery Act (RCRA) for the management of solid wastes, the Clean Air Act (CAA) for controlling air emissions, and the Clean Water Act (CWA) for discharges into water bodies. States can impose more stringent regulatory standards than required by these federal statutes. Counties and local municipalities may also impose requirements under their own authority, including building and siting codes.

There may or may not be separate regulations for conversion technologies and conventional WTE technologies in some jurisdictions. An example is Oregon, which considers conversion technology facilities to be solid waste disposal sites and has specific permitting requirements for conversion technology facilities. Other states may have additional requirements, such as California and New York, that require conversion technologies (gasification and pyrolysis) to use MSW-based feedstock in order to qualify for credits under the renewable portfolio standards.

Information presented below was gathered from available information from state regulatory authorities.

Facility	State	Technology	Identified Permits
Agilyx	OR	Pyrolysis	Simple Air Contaminant Discharge Permit[75]
Nexus	GA	Pyrolysis	Air Quality Permit (Type: State Implementation Plan (SIP) Permit) as an alternative fuel product manufacturing facility[76]
Renewlogy	UT	Pyrolysis	Considered a "small emitter" thus exempt from air permitting requirements. No waste related permits.
Fulcrum Bioenergy	NV	Gasification	Class II Air Quality Operating Permit.[77] The MSW processing operation is permitted as a material recovery facility.
Fort Hunter Liggett Sierra Energy	CA	Gasification	Received approvals from the Monterey Bay Unified Air Pollution Control District and the Regional Water Quality Control Board. Received an exemption from solid waste permitting requirements, primarily because it is a resource recovery facility intended only for demonstration purposes and not for profit, and that the facility is funded primarily by government grants.[78]

Permitting conversion technologies can be challenging as their discharge may be covered under different environmental statutes and be subject to different regulations from the federal government through the local municipality. This makes permitting a new facility a challenging and can result in a lengthy endeavor often taking several years. As conversion technologies may design innovative and cutting-edge operating systems, for example, public authorities rarely have a precedent on which to base permitting decisions on or knowing which permits and licenses to apply for and get approval. Permitting classifications can also depend on whether MSW is preprocessed on- or off-site.

There may also be state or local odor control requirements. Odors are a concern for facilities that handle MSW-based feedstock, particularly food and organic wastes. Odors can occur when unloading incoming

[75] OR DEQ Facility Profiler. https://www.deq.state.or.us/msd/profilerreports/traacs.asp?id=34-9514-SI-01
[76] Georgia Air Permit Search Engine. https://permitsearch.gaepd.org/
[77] NDEP Air Records Search. https://documentviewerpublic.ndep.nv.gov/Common/Login.aspx?ReturnUrl=%2f
[78] CalRecycle SWIS Facility Detail. Municipal Solid Waste to Energy Project (27-AA-0123) https://www2.calrecycle.ca.gov/swfacilities/Directory/27-AA-0123

feedstock, pretreatment holding tanks, storage areas, disposal as well as during the processes (e.g., shredding, grinding and sizing, opening AD chambers).

A number of vendors may advertise that their technology has the ability to reuse processed solid waste and wastewater streams as feedstocks and in their process, but there may be differences by regulators as to how these activities are permitted and under what statutes (e.g., Title V Permits, Water Quality Permits, state land permits, industrial user permit to a WRRF).

In terms of permitting at the federal level, under the Clean Air Act, large conversion plants will likely be required to obtain a Prevention of Significant Deterioration (PSD) permit, if the plant will be located in an area that is meeting the National Ambient Air Quality Standards (NAAQS), or a Nonattainment New Source Review (NNSR) permit, if it will be located in an area that is not meeting the NAAQS. For new Integrated Gasification Combined Cycle (IGCC) plants, for example, PSD and NNSR permits often require companies to spend a minimum of three months to prepare their applications and up to an additional 12 months for the approval of the permits. Except for Indian Country and states without approved PSD programs, PSD and NNSR permits are issued by states subject to EPA oversight. For example, since Illinois does not currently have an EPA-approved PSD program, Illinois issues PSD permits under a delegation agreement with EPA.

In two cases reviewed by the EPA in Illinois, one company, GreenSmith Environmental, that applied for a Clean Air Act permit spent over 14 months and 10 months on their application and EPA review respectively. Another company, Taylorville Energy Center spent over 10 months and 22 months on their application and EPA review respectively.

7.4 Additional Considerations

Technology vendors identified and reviewed as part of this report often demonstrated a strong dependence on technical institutional, academic and government support to design, build and operate their conversion technology project to maximum efficiency. Gasification and pyrolysis companies face a variety of economic, legal, contractual, and political challenges to realizing a successful and sustainable operation. In addition to securing specific feedstock and product off-take agreements, companies may also actively seek to establish their plants in locations with high disposal fees. A company or a hauler would want to take the material for disposal to the least costly facility, and by having competitive or lower rates than other non-sustainable disposal options, may influence waste producers to use more sustainable waste management and recovery practices. Other considerations to locations include those with high natural gas prices (that would provide their alternative fuels with a competitive edge—due to lower production costs) and the ability to complement existing electricity infrastructure (e.g., steam turbine generators that are connected to national grid).

AD companies reviewed as part of this study also highlighted the role of institutional, technical and government support to realize a cost-efficient design, operational facility, and maintenance over time. The provision of having solid waste and wastewater feedstock agreements, a power purchase agreement, a design supply agreement with the technology provider, multiple construction contracts and an operation and maintenance agreement in place were all noted as important factors to attract investment and establishing a successful AD business operation.

- Companies, including, Zero Waste Energy Development Company (ZWEDC) and Blue Line Biogenic compressed natural gas facility that both operated dry fermentation anaerobic digestion plants sought out exclusive guarantees for organic municipal waste supply/feedstock by the City of San Jose and San Francisco, respectively, through 10 to 15-year organic feedstock supply agreements. An additional company, CR&R secured municipal solid waste feedstock supply agreements in Temecula, Wildomar, Lake Elsinore, Perris, Hemet, Calimesa, Riverside County, San Jacinto and Canyon Lake, California, prior to constructing their plants.

- An increasing trend for AD system companies is to partner with several ancillary business operations, to ensure continuing economic success. For example, if one of the end products is a sellable gas, AD systems have contracts with a hauling company or bus company that uses renewable fuels. AD systems have also partnered with other companies to take a continuous stream of feedstock (cheese operations), for example.

AD companies similarly highlighted a variety of legal and political challenges to realizing a more cost-efficient operation. Specific examples may include the simplification of permitting requirements and guidance for existing or innovative AD system trials and pilot tests. An area that AD companies noted that was helpful to establish their facility was in states with active food waste bans from landfills or food diversion ordinances and programs. Such ordinances and programs exist in several states including in California, Connecticut, Vermont, Massachusetts, and Rhode Island and in cities, including, Austin, San Antonio, Madison, Los Angeles, New York City, San Francisco, Seattle, Denver, Portland and Ann Arbor. Such legal measures assist the AD operators in obtaining the supply and organic inputs they require in urban areas. For example, the CRMC Bioenergy Project that serves Dartmouth and New Bedford, Massachusetts, met its feedstock targets by providing one of the only legal methods for businesses to send their organic waste following the state-wide ban on the disposal of commercial food waste and other organics into landfills.

7.7 Key Data Gaps and Recommendations for Future Research

Making direct comparisons of different conversion technologies and conventional technologies is challenging, in part due to differences among the processes and lack of operating data for characterizing cost and environmental performance. While operating data may be more readily available in other regions of the world, such as Europe, there is a need for operating data for facilities in the US to better assess their performance and demonstrate their potential to the US market. Other technologies such as chemical recycling and mechanical biological treatment should also be included in future evaluations.

Additional research that could be done to advance the understanding of conversion technologies might include examining data for operating conversion facilities outside of the US and sensitivities of these technologies relative to cost and environmental aspects for key parameters such as:

- feedstock composition (e.g., high vs. low heating value feedstock, biomethane potential),
- feedstock preprocessing requirements and associated cost and energy use,
- energy conversion efficiency and net energy production,
- post-processing requirements for end-products (e.g., syngas cleaning),
- recovery of materials for recycling (for mixed MSW technologies),
- beneficial offsets for different by-products,
- market prices for end-products, and
- market prices for recyclable and other byproduct streams.

Additional guidance is needed to better understand permitting requirements for conversion technologies. Case studies highlighting permitting challenges and successful solutions would provide useful information for communities.

On-going technology and innovations in the process designs, feedstocks and operating models will continue to make the conversion technology sector dynamic and therefore updates to guidance and recommendations can be expected. Changes in economics could occur if carbon reductions are required resulting in some of these technologies being more attractive in the ability to minimize carbon emissions while maximizing resource (including nutrients from food and yard waste) and energy recovery from residential and commercial waste.

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Attachment A:
Listing of Waste-To-Energy Facilities in the US

Primary Sources:

Michaels and Shiang. 2016. 2016 Directory of Waste-To-Energy Facilities. http://energyrecoverycouncil.org/wp-content/uploads/2016/05/ERC-2016-directory.pdf

US Energy Information Administration. EIA-860, Annual Electric Generator Report, 2017. https://www.eia.gov/electricity/data/eia860/

technology type	**Site name**	**Operator**	**City**	**State**	**Included as a WTE facility in the US EIA 2017 Electric Generator Report**
mass burn	Huntsville Waste-to-Energy Facility	Covanta Huntsville, Inc	Huntsville	AL	No. The generated steam goes to the U.S. Army's Redstone Arsenal.
mass burn	Southeast Resource Recovery Facility	Covanta Long Beach Renewable Energy Corp.	Long Beach	CA	yes
mass burn	Stanislaus County Resource Recovery Facility	Covanta Stanislaus, Inc.	Crows	CA	yes
mass burn	Bristol Resource Recovery Facility	Covanta Bristol, Inc.	Bristol	CT	yes
RDF	Mid-Connecticut Resource Recovery Facility	NAES Corp.	Harford	CT	yes
mass burn	Southeastern Connecticut Resource Recovery Facility	Covanta Company Southeastern CT	Preston	CT	yes
mass burn	Wheelabrator Bridgeport	Wheelabrator Bridgeport, L.P.	Bridgeport	CT	yes
mass burn	Wheelabrator Lisbon	Wheelabrator Lisbon, Inc.	Lisbon	CT	yes
mass burn	Bay County Waste-to-Energy Facility	Engen, LLC	Panama City	FL	yes
mass burn	Hillsborough County Resource Recovery Facility	Covanta Hillsborough, Inc.	Tampa	FL	yes
mass burn	Lake County Resource Recovery Facility	Covanta lake, Inc.	Okahumpka	FL	yes
mass burn	Lee County Resource Recovery Facility	Covanta Lee, Inc.	Fort Meyers	FL	yes
RDF	Miami-Dade County Resource Recovery Facility	Covanta Dade Renewable Energy, LLC	Miami	FL	yes
RDF	Palm Beach Renewable Energy Facility #1	Babcock & Wilcox	West Palm Beach	FL	yes
mass burn	Palm Beach Renewable Energy Facility #2	Babcock & Wilcox	West Palm Beach	FL	yes
mass burn	Pasco County Solid Waste Resource Recovery	Covanta Pasco, Inc.	Spring Hill	FL	yes
mass burn	Pinellas County Resource Recovery Facility	Covanta Pinellas, Inc.	St. Petersburg	FL	yes

technology type	Site name	Operator	City	State	Included as a WTE facility in the US EIA 2017 Electric Generator Report
mass burn	McKayBay Refuse-to-Energy Facility	Wheelabrator Mckay Bay, Inc.	Tampa	FL	yes
mass burn	Wheelabrator South Broward, Inc.	Wheelabrator South Broward, Inc.	Ft. Lauderdale	FL	yes
RDF mass burn	Honolulu Resource Recovery Venture- HPOWER	Covanta Honolulu Resource Recovery Venture	Kapolei	HI	yes
mass burn	Indianapolis Resource Recovery Facility	Covanta Indianapolis, Inc.	Indianapolis	IN	yes
RDF	Arnold O. Chantland Resource Recovery Plant (also called the Ames Resource Recovery Plant)	City of Ames	Ames	IA	No. The Ames Electric Services Power Plant is included, and it burns RDF from the Ames Resource Recovery Plant
mass burn	Regional Waste Systems	Ecomaine	Portland	ME	yes
mass burn	Mid-Maine Waste Action Corporation	Mid-Maine Waste Action Corporation	Auburn	ME	yes
RDF	Penobscot Energy Recovery Company	ESOCO Orrington, LLC	Orrington	ME	yes
mass burn	Montgomery County Resource Recovery Facility	Covanta Montgomery, Inc.	Dickerson	MD	yes
mass burn	Wheelabrator Baltimore	Wheelabrator Baltimore, L.P.	Baltimore	MD	yes
mass burn	Haverhill Resource Recovery Facility	Covanta Haverhill, Inc.	Haverhill	MA	yes
Modular	Pioneer Valley Resource Recovery Facility	Covanta Springfield, LLC	Agawam	MA	yes
RDF	SEMASS Resource Recovery Facility	Covanta SEMASS, L.P.	West	MA	yes
mass burn	Wheelabrator Millbury	Wheelabrator Millbury, Inc.	Millbury	MA	yes
mass burn	Pittsfield Resource Recovery Facility	Covanta Pittsfield, LLC	Pittsfield	MA	yes
mass burn	Wheelabrator North Andover	Wheelabrator North Andover, Inc.	North Andover	MA	yes
mass burn	Wheelabrator Saugus	Wheelabrator Saugus, Inc.	Saugus	MA	yes
RDF	Detroit Renewable Power	Detroit Renewable Energy, LLC	Detroit	MI	yes
mass burn	Kent County Waste-to-Energy Facility	Covanta Kent, Inc.	Grand Rapids	MI	yes
mass burn	Hennepin Energy Resource Center (HERC)	Covanta Hennepin Energy Resource	Minneapolis	MN	yes
mass burn	Olmsted Waste-to-Energy Facility (OWEF)	Olmsted County	Rochester	MN	yes
mass burn	Perham Resource Recovery Facility	Prairie Lakes Municipal Solid Waste	Perham	MN	yes
Modular	Polk County Solid Waste Resource Recovery Facility	Polk County	Fosston	MN	No. The steam goes to 3 nearby customers
mass burn	Pope/Douglas Waste-to-Energy Facility	Pope/Douglas Solid Waste Point Powers Board	Alexandria	MN	No. The steam is used by a 3M manufacturing plant, a nearby hospital, and school.
RDF	Red Wing Steam Plant	Northern States Power Co - Minnesota	Red Wing	MN	yes

technology type	Site name	Operator	City	State	Included as a WTE facility in the US EIA 2017 Electric Generator Report
RDF	Wilmarth Plant	Northern States Power Co - Minnesota	Mankato	MN	yes
mass burn	Wheelabrator Concord	Wheelabrator Concord, L.P.	Penacook	NH	yes
mass burn	Covanta Camden Energy Recovery Center	Covanta Camden GP, LLC	Camden	NJ	yes
mass burn	Essex County Resource Recovery Facility	Covanta Essex Company	Newark	NJ	yes
mass burn	Union County Resource Recovery Facility	Covanta Union, LLC	Rahway	NJ	yes
mass burn	Wheelabrator Gloucester Company	Wheelabrator Gloucester Company, L.P.	Westville	NJ	yes
mass burn	Babylon Resource Recovery Facility	Covanta Babylon, Inc.	West Babylon	NY	yes
mass burn	Covanta Hempstead	Covanta Hempstead Co.	Westbury	NY	yes
mass burn	Dutchess County Resource Recovery Facility	Wheelabrator Dutchess County	Poughkeepsie	NY	yes
mass burn	Huntington Resource Recovery Facility	Covanta Huntington	East Northport	NY	yes
mass burn	MacArthur Waste-to-Energy Facility	Covanta MacArthur Renewable Energy,	Ronkonkoma	NY	yes
mass burn	Niagara Falls Resource Recovery Facility	Covanta Niagara company	Niagara Falls	NY	yes
mass burn	Onondaga Resource Recovery Facility	Covanta Onondaga, L.P.	Jamesville	NY	yes
Modular	Oswego County Energy Recovery Facility	Oswego County	Fulton	NY	yes
mass burn	Wheelabrator Hudson Falls	Wheelabrator Hudson Falls, LLC	Hudson Falls	NY	yes
mass burn	Wheelabrator Westchester	Wheelabrator Westchester, L.P.	Peekskill	NY	yes
Mass Burn	Covanta Tulsa Renewable Energy Facility	Covanta Tulsa Renewable Energy, LLC	Tulsa	OK	yes
mass burn	Marion County Solid Waste-to-Energy Facility	Covanta Marion, Inc.	Brooks	OR	yes
mass burn	Covanta Plymouth Renewable Energy	Covanta Plymouth Renewable Energy	Conshohocken	PA	yes
mass burn	Delaware Valley Resource Recovery Facility	Covanta Delaware Valley, L.P.	Chester	PA	yes
mass burn	Lancaster County Resource Recovery Facility	Covanta Lancaster, Inc.	Bainbridge	PA	yes
mass burn	Susquehanna Resource Management Complex	Covanta Harrisburg, Inc.	Harrisburg	PA	yes
mass burn	Wheelabrator Falls	Wheelabrator Falls Inc.	Morrisville	PA	yes
mass burn	York County Resource Recovery Center	Covanta York Renewable Energy LLC	York	PA	yes
mass burn	Alexandria/Arlington Resource Recovery Facility	Covanta Arlington/Alexandria, Inc.	Alexandria	VA	yes
mass burn	Hampton-NASA Steam Plant	City of Hampton	Hampton	VA	No. The steam is used directly by NASA
mass burn	I-95 Energy/Resource Recovery Facility (Fairfax)	Covanta Fairfax, Inc.	Lorton	VA	yes
RDF	Wheelabrator Portsmouth	Wheelabrator Portsmouth Inc.	Portsmouth	VA	yes
Mass Burn	Spokane Waste-to-Energy Facility	City of Spokane	Spokane	WA	yes
Modular	Truman Barron County Waste-to-Energy & Recycling Facility		Almena	WI	No. The steam goes to Saputo Cheese

technology type	Site name	Operator	City	State	Included as a WTE facility in the US EIA 2017 Electric Generator Report
RDF	French Island Generating Station	Northern States Power Co - Minnesota	La Crosse	WI	No. Categorized as combusting wood/wood waste biomass.
Facilities that have recently closed					
RDF	Great River Energy - Elk River Station	Great River Energy	Maple Grove	MN	Yes. Closed 2019[79]
mass burn	Covanta Warren Energy Resource Facility	Covanta Warren Energy Resource Co.	Oxford	NJ	Yes. Closed 2019.[80]
mass burn	Commerce Refuse-to-Energy Facility	Sanitation District of Los Angeles	Commerce	CA	Yes, but then closed June 2018
mass burn	Davis Energy Recovery Facility	Wasatch Integrated Waste Management	Layton	UT	No. Closed May 2017

[79] EE Online. *Great River Energy: Elk River project stops operations, prepares for closure.* Feb. 25, 2019. https://electricenergyonline.com/article/energy/category/biofuel/83/750958/elk-river-project-stops-operations-prepares-for-closure.html

[80] Lehighvalleylive.com *Covanta has shut down its Warren County trash incinerator. But it might not be permanent.* 4 April 2019. https://www.lehighvalleylive.com/warren-county/2019/04/covanta-has-shut-down-its-warren-county-trash-incinerator-but-it-might-not-be-permanent.html

Attachment B:
Listing of Stand-Alone and Co-Digestion Facilities in the US

Stand-Alone Facilities	Location	Multi-Source (MS)/Industry-Dedicated (ID)/Other*
Facilities currently operating		
Ralphs Recovery System	Compton, CA	ID
Fairfield Brewery BTS	Fairfield, CA	ID
MillerCoors Brewery	Irwindale, CA	ID
Zero Waste Energy -Monterey	Marina, CA	MS
North State Rendering Co. Inc./John S. Ottone	Oroville, CA	MS
Gills Onions	Oxnard, CA	ID
CleanWorld SATS	Sacramento, CA	MS
Kompogas SLO LLC	San Luis Obispo, CA	MS
Zero Waste Energy Development Company	San Jose, CA	MS
Blue Line Biogenic CNG Facility	South San Francisco, CA	MS
LA BTS	Van Nuys, CA	ID
Quantum Biopower	Southington, CT	MS
Harvest Power Orlando	Bay Lake, FL	MS
Jacksonville BTS	Jacksonville, FL	ID
Cartersville BTS	Cartersville, GA	ID
City of Waterloo Anaerobic Lagoon	Waterloo, IA	OTHER
Waste No Energy, LLC	Monticello, IN	MS
Stop & Shop Freetown Distribution Center	Assonet, MA	ID
Garelick Farms	Franklin, MA	ID
CRMC Bioenergy Facility	New Bedford, MA	OTHER
Generate Fremont Digester, LLC	Fremont, MI	MS
Hometown BioEnergy	Le Sueur, MN	MS
St. Louis BTS	St. Louis, MO,	ID
Full Circle Recycle	Zebulon, NC	MS
Merrimack BTS	Merrimack, NH	ID
Newark BTS	Newark, NJ	ID
Lassonde Pappas	Seabrook, NJ	ID
AB-Inbev Baldwinsville	Baldwinsville, NY	ID
Buffalo BioEnergy	West Seneca, NY	MS
Generate Niagara Digester	Wheatfield, NY	MS
Emerald BioEnergy	Cardington, OH	MS
Collinwood BioEnergy	Cleveland, OH	OTHER
Central Ohio BioEnergy	Columbus, OH	MS
Columbus BTS	Columbus, OH	ID
Dovetail Energy	Fairborn, OH	MS
Campbell Soup Supply Company	Napoleon, OH	ID
Three Creek BioEnergy, LLC	Sheffield Village, OH	MS
Buckeye Biogas, LLC	Wooster, OH	MS
Zanesville Energy, LLC	Zanesville, OH	MS
Stahlbush Island Farms	Corvallis, OR	OTHER
Yuengling Beer Company	Pottsville, PA	ID

Stand-Alone Facilities	Location	Multi-Source (MS)/Industry-Dedicated (ID)/Other*
Bush Brothers and Company Process Water Recovery	Dandridge, TN	ID
Houston BTS	Houston, TX	ID
Magic Hat Resource Recovery Center	South Burlington, VT	MS
FCPC Renewable Generation	Milwaukee, WI	MS
Urban Dry Digester – UW Oshkosh	Oshkosh, WI	MS
Facilities Under Development		
CleanWorld/UC Davis Renewable Energy Anaerobic	Davis, CA	Temporary Shut-Down
Agromin Organic Recycling Compost Facility	Oxnard, CA	Planning stage; Design
Organic Energy Systems (OES)	San Bernardino, CA	Procurement
Tajiguas Resource Recovery Project	Santa Barbara, CA	Planning stage; Design
Turning Earth LLC	Southington, CT	Fully permitted, seeking
BTS Biogas LLC -Maryland Food Center	Jessup, MD	Under Construction
Orbit Energy Charlotte	Charlotte, NC	Start-up Mode
Linden Renewable Energy	Linden, NJ	Planning stage; Design
Gloucester City Organic Recycling	Marlton, NJ	Under Construction
Point Breeze Renewable Energy	Philadelphia, PA	Planning stage; Design
Orbit Energy Rhode Island	Johnston, RI	Start-up Mode
Freestate Farms Integrated Facility	Manassas, VA	Planning stage; Design
Facilities That Have Ceased Operations		
Heartland Biogas	LaSalle, CO	
CR&R	Perris, CA	
Garelick Farms	Lynn, MA	

* "OTHER" represents two industry dedicated digesters that accept outside feedstocks periodically.

1. **Source: US EPA, 2019**

On-Farm Digesters Co-Digesting Food Waste	Location
Facilities Currently Operating	
Green Cow Power	Goshen, IN
BioTown Ag	Reynolds, IN
Rutland AD1	Rutland, MA
Exeter Agri-Energy/Stonyvale Farm	Exeter, ME
Patterson Farms Inc.	Auburn, NY
Noblehurst Green Energy	Linwood, NY
Oregon Dairy Farm LLC	Lititz, PA
Reinford Farms	Mifflintown, PA
Oak Hill Farm	Nottingham, PA
Chaput Family Farms	North Troy, VT
Vermont Technical College Anaerobic Digester	Randolph Center, VT
Vander Haak Dairy	Lynden, WA
Qualco Energy	Monroe, WA
Holsum Elm Dairy	Hilbert, WI
Holsum Irish Dairy	Hilbert, WI
Allen Farms	Oshkosh, WI
Facilities That Have Ceased Operations	
Zuber Farms	Byron, NY

On-Farm Digesters Co-Digesting Food Waste	Location
George Deruyter Dairy	Outlook, WA
Wild Rose Dairy	LaFarge, WI

Source: US EPA, 2019

Co-Digestion at WWTP Facilities	Location
Facilities Currently Operating	
Fourche Creek Water Reclamation Facility	Little Rock, AR
Wildcat Hill Wastewater Treatment Plant	Flagstaff, AZ
Delta Diablo WWTP	Antioch, CA
Bakersfield Wastewater Treatment Plant # 2	Bakersfield, CA
Bakersfield Wastewater Treatment Plant # 3	Bakersfield, CA
Hill Canyon Wastewater Treatment Plant	Camarillo, CA
Encina Wastewater Authority (EWPCF)	Carlsbad, CA
Joint Water Pollution Control Plant	Carson, CA
Sacramento Regional Wastewater Treatment Plant	Elk Grove, CA
Fairfield-Suisun Sewer District	Fairfield, CA
Fresno-Clovis RWRF	Fresno, CA
City of Hayward Water Pollution Control Facility	Hayward, CA
Napa Sanitation District	Napa, CA
East Bay Municipal Utility District Main Wastewater Treatment Plant	Oakland, CA
Silicon Valley Clean Water	Redwood City, CA
Oro Loma Sanitary District	San Lorenzo, CA
Central Marin Sanitation Agency	San Rafael, CA
El Estero WWTP	Santa Barbara, CA
Santa Rosa Regional Water Reuse Plant (Laguna Treatment Plant)	Santa Rosa, CA
Victor Valley Wastewater Reclamation Authority	Victorville, CA
City of Watsonville WWTP	Watsonville, CA
Santa Rita Wastewater Reclamation Plant (City of Durango WWTP)	Durango, CO
South Cross Bayou Advanced Water Reclamation Facility	St. Petersburg, FL
Thomas P Smith Water Reclamation Facility (TPS Treatment Plant)	Tallahassee, FL
F. Wayne Hill Water Resources Center	Buford, GA
South Columbus Water Treatment Facility	Columbus, GA
Lower Poplar Street Water Reclamation Facility	Macon, GA
Ames Water Pollution Control Plant	Ames, IA
Davenport Water Pollution Control Plant	Davenport, IA
Des Moines Metropolitan Wastewater Reclamation Authority	Des Moines, IA
Dubuque Water & Resource Recovery Center	Dubuque, IA
Downers Grove Sanitary District Wastewater Treatment Center	Downers Grove, IL
Rock River Water Reclamation District	Rockford, IL
Urbana & Champaign Sanitary District	Urbana, IL
West Lafayette Wastewater Treatment Facility	West Lafayette, IN
DLS Middle Basin Wastewater Treatment Plant	Overland Park, KS
Greater Lawrence Sanitary District	North Andover, MA
Lewiston-Auburn Water Pollution Control Authority	Lewiston, ME
Delhi Charter Township Wastewater Treatment Plant	Holt, MI
Flint Biogas Plant	Flint, MI
St. Cloud Nutrient, Energy and Water Recovery Facility	St. Could, MN

Co-Digestion at WWTP Facilities		Location
City of Springfield Southwest Wastewater Treatment Plant		Springfield, MO
Joint Meeting of Essex & Union Counties		Elizabeth, NJ
Rahway Valley Sewerage Authority		Rahway, NJ
Landis Sewerage Authority		Vineland, NJ
Newtown Creek Wastewater Resource Recovery Facility		Brooklyn, NY
LeRoy R. Summerson Wastewater Treatment Facility		Cortland, NY
Gloversville Johnstown Joint Wastewater Treatment Facility		Johnstown, NY
City of London Wastewater Treatment Plant		London, OH
City of Wooster Water Resource Recovery Facility		Wooster, OH
Gresham Wastewater Treatment Plant		Gresham, OR
City of Pendleton Wastewater Treatment Facility		Pendleton, OR
Clean Water Services -Durham Advanced Wastewater Treatment Facility		Tigard, OR
Hermitage Municipal Authority		Hermitage, PA
Derry Township Municipal Authority		Hershey, PA
Milton Regional Sewer Authority		Milton, PA
New Castle Sanitation Authority		New Castle, PA
Mauldin Road Water Resource Recovery Facility		Greenville, SC
Southside Wastewater Treatment Plant		Dallas, TX
Waco Metro -Area Regional Sewage System		Waco, TX
North River Wastewater Treatment Facility		Mt. Crawford, VA
Opequon Water Reclamation Facility		Winchester, VA
Village of Essex Junction Water Resource Recovery Facility		Essex Junction, VT
Appleton Wastewater Treatment Plant		Appleton, WI
Fond du Lac Regional Wastewater Treatment & Resource Recovery Facility		Fond du Lac, WI
City of Kiel Wastewater Facility		Kiel, WI
MMD South Shore Water Reclamation Facility		Oak Creek, WI
City of Port Washington Wastewater Treatment Plant		Port Washington, WI
City of Rice Lake Wastewater Treatment Plant		Rice Lake, WI
Stevens Point Wastewater Treatment Plant		Stevens Point, WI
City of West Bend Wastewater Treatment Plant		West Bend, WI
Wisconsin Rapids Wastewater Treatment Facility		Wisconsin Rapids, WI
Facilities Under Development		
South Slope Wastewater Treatment Plant	Planning stage; Design stage;	Moline, IL
Kinross Township Wastewater Treatment Plant	Under Construction	Kincheloe, MI
Western Lake Superior Sanitary District	Planning stage; Design stage;	Duluth, MN
Empire Wastewater Treatment Plant	Under Construction	Farmington, MN
Village of Ridgewood Water Pollution Control Facility	Temporary Shut-down	Glen Rock, NJ
Rome Water Pollution Control Facility	Planning stage; Design stage;	Rome, NY
City of Newark Wastewater Treatment Plant	Temporary Shut-down	Newark, OH
Green Bay Metropolitan Sewerage District	Under Construction	Green Bay, WI
Facilities That Have Ceased Operations		
Hyperion Treatment Plant		Playa Del Rey, CA
Metropolitan Syracuse Wastewater Treatment Plant		Syracuse, NY
Struthers Wastewater Treatment Plant		Struthers, OH
Janesville Wastewater Treatment Plant		Janesville, WI
Sheboygan Wastewater Treatment Plant		Sheboygan, WI

Source: US EPA, 2019

Attachment C: Definitions

Anaerobic Digestion (AD) – decomposition of biodegradable waste in oxygen depleted conditions to biogas and solid residue (digestate)[81]

Conversion technologies – waste treatment technologies that do not directly combust MSW feedstock but rather convert it via partial-oxygen or oxygen absent thermochemical or biological processes. The resulting gases can be combusted to produce electricity or further processed into a liquid fuel or chemical commodity product.

Energy recovery -- conversion of waste materials into usable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolysis, anaerobic digestion and landfill gas recovery.

Gasification –thermal decomposition of waste in a controlled oxygen environment that converts any material containing carbon – such as coal, petroleum or biomass – into synthesis gas (syngas) composed of hydrogen and carbon monoxide. The syngas can be then burned to produce electricity or further processed to produce vehicle fuel.[82]

Mass burn combustion (or waste to energy) –burning of MSW in a confined and controlled environment, typically in a single combustion chamber under conditions of excess air, to produce steam that is used to generate electricity or combined heat and power[83]. Mass burn often includes recovery of ferrous and other metals prior to disposal of combustion ash.

Material Recovery Facility: a facility where comingled recycling streams and/or solid waste is sorted to recover materials for recycling.[84]

MSW Landfill: an entire disposal facility in a contiguous geographical space where household waste is placed in or on land. An MSW landfill may also receive other types of RCRA Subtitle D wastes (§ 257.2 of this title) such as commercial solid waste, nonhazardous sludge, conditionally exempt small quantity generator waste, industrial solid waste and coal combustion residuals.

Municipal Solid Waste: discards from residential and commercial sources that include durable and nondurable goods including paper, plastic glass, metal, food scraps, yard trimmings, and other inorganic and organic materials. MSW does not contain regulated hazardous wastes. (MSW = Residential + Commercial), U.S. EPA National Measurement Workgroup, 2013.[85]

Organic Materials: the remains, residues or waste products of any organic materials that are components of the solid waste disposal stream. Such materials may include but are not limited to food residuals; yard debris; and wood, plant or paper products. This term does not include metals, glass, or petroleum-based plastic (U.S. EPA National Measurement Workgroup, 2013).

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[81] Gershman, Brickner & Bratton, Inc. Presentation for Arizona Tribal Energy Association on Waste to Energy Technologies. January 2018

[82] EPA Webpage https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw

[83] EPA Webpage https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw

[84] UC Berkeley School of Law. "Wasting Opportunities: How to Secure Environmental & Clean Energy Benefits from Municipal Solid Waste Energy Recovery." May 2016

[85] US EPA. State Measurement Template Definitions. https://www.epa.gov/sites/production/files/2015-09/documents/smp_definitions.pdf

Pyrolysis – an endothermic process, also referred to as cracking, using heat to thermally decompose carbon-based material in the absence of oxygen, into pyrolysis oil, syngas, and other byproducts (such as char, tar or flue gas) .[86]

Refuse-derived fuel –mechanically shredded MSW that is processed to separate out non-combustible materials and produce a combustible mixture in loose or pelletized form that is suitable as a fuel in a dedicated furnace or as a supplemental fuel in a conventional boiler system.[87]

Syngas – synthesis gas, produced by gasification or pyrolysis, which is composed of hydrogen, carbon monoxide and carbon dioxide.[88]

[86] UC Berkeley School of Law. "Wasting Opportunities: How to Secure Environmental & Clean Energy Benefits from Municipal Solid Waste Energy Recovery." May 2016.
[87] EPA Webpage https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw
[88] UC Berkeley School of Law. "Wasting Opportunities: How to Secure Environmental & Clean Energy Benefits from Municipal Solid Waste Energy Recovery." May 2016.

Attachment D:
Pyrolysis Life Cycle Inventory Data Compiled from the Literature

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Input	n/a	Aggregate	kg	11.6	11.6	11.6
Input	n/a	Air	kg	400	400	400
Input	n/a	Aluminium	kg	0.0016	0.0016	0.0016
Input	n/a	Calcium oxide	kg	46.0	46.0	46.0
Input	n/a	Chromium	kg	0	0	0
Input	n/a	Clay	kg	3.95	3.95	3.95
Input	n/a	Copper	kg	0.0015	0.0015	0.0015
Input	n/a	Electricity	MJ	0.21	810	1,620
Input	n/a	Fossil energy	MJ	1,040	2,872	3,910
Input	n/a	Iron	kg	0.0091	0.0091	0.0091
Input	n/a	Limestone, calcium carbonate	kg	10.9	10.9	10.9
Input	n/a	Manganese	kg	0	0	0
Input	n/a	Naphtha	MJ	131	131	131
Input	n/a	Ni catalyst	kg	0.19	0.19	0.19
Input	n/a	Nickel	kg	0	0	0
Input	n/a	Pyrite	kg	0	0	0
Input	n/a	Rock	kg	65.7	65.7	65.7
Input	n/a	Sand	kg	0.0099	4.25	8.50
Input	n/a	Sodium chloride	kg	0.010	0.010	0.010
Input	n/a	Soil	kg	0.24	0.24	0.24
Input	n/a	Water	kg	0	1,271	3,300
Input	n/a	Zeolite	kg	1.20	1.20	1.20
Input	n/a	Zinc	kg	0	0	0
Output	(blank)	Calcium chloride	kg	17.0	17.0	17.0
Output	(blank)	Calcium oxide	kg	40.0	40.0	40.0
Output	air	Ammonia	kg	0	0	0
Output	air	Argon	kg	11.7	11.7	11.7

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	air	Butadiene	kg	0.67	0.67	0.67
Output	air	Butane	kg	1.88	1.88	1.88
Output	air	Butene	kg	0.80	0.80	0.80
Output	air	Carbon dioxide	kg	370	730	1,090
Output	air	Carbon monoxide	kg	0.18	14.8	29.5
Output	air	Ethane	kg	0.94	0.94	0.94
Output	air	Formic acid	kg	3.2E-05	3.2E-05	3.2E-05
Output	air	GHG, biogenic (CO2 eq)	kg	1,035	1,035	1,035
Output	air	GHG, fossil (CO2 eq)	kg	230	240	250
Output	air	Hydrocarbons, unspecified	kg	5.5E-05	5.5E-05	5.5E-05
Output	air	Hydrogen	kg	0	1.34	2.68
Output	air	Hydrogen sulphide	kg	0.012	0.012	0.012
Output	air	Iron	kg	1.6E-05	1.6E-05	1.6E-05
Output	air	Lead	kg	5.0E-06	5.0E-06	5.0E-06
Output	air	Manganese	kg	6.1E-06	6.1E-06	6.1E-06
Output	air	Mercury	kg	1.3E-06	1.3E-06	1.3E-06
Output	air	Methane	kg	0.14	6.77	13.4
Output	air	Methane, biogenic	kg	3.0E-05	3.0E-05	3.0E-05
Output	air	Nickel	kg	2.8E-06	2.8E-06	2.8E-06
Output	air	Nitrogen	kg	310	310	310
Output	air	Nitrogen dioxide	kg	3.7E-05	3.7E-05	3.7E-05
Output	air	Nitrogen monoxide	kg	0	0	0
Output	air	Nitrogen oxides	kg	0.39	0.39	0.39
Output	air	Nitrogen, atmospheric	kg	4,350	4,350	4,350
Output	air	Nitrogentriflouride	kg	0	0	0
Output	air	Nitrous oxide	kg	0	0	0
Output	air	NMVOC	kg	0.016	0.016	0.016

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	air	Oxygen	kg	60.0	3,925	7,790
Output	air	Particles	kg	0.013	0.013	0.013
Output	air	PM 10	kg	4.9E-04	4.9E-04	4.9E-04
Output	air	PM 2.5	kg	3.3E-04	3.3E-04	3.3E-04
Output	air	Propane	kg	1.88	1.88	1.88
Output	air	Propene	kg	1.34	1.34	1.34
Output	air	Selenium	kg	4.7E-06	4.7E-06	4.7E-06
Output	air	Steam	kg	330	330	330
Output	air	Sulphur	kg	0	0	0
Output	air	Sulphur dioxide	kg	0.44	0.44	0.44
Output	air	Tin	kg	4.1E-06	4.1E-06	4.1E-06
Output	air	Titanium	kg	9.1E-06	9.1E-06	9.1E-06
Output	air	Vanadium	kg	6.4E-06	6.4E-06	6.4E-06
Output	air	VOC, unspecified	kg	0	0	0
Output	air	Water	kg	240	240	240
Output	air	Zinc	kg	9.1E-06	9.1E-06	9.1E-06
Output	energy	Steam	MJ	1,480	1,480	1,480
Output	fresh water	Aluminium	kg	0.74	0.74	0.74
Output	fresh water	Ammonia	kg	1.2E-04	1.2E-04	1.2E-04
Output	fresh water	Ammonium	kg	0	0	0
Output	fresh water	Antimony	kg	0.017	0.017	0.017
Output	fresh water	Barium	kg	1.1E-04	1.1E-04	1.1E-04
Output	fresh water	BOD	kg	1.17	1.17	1.17
Output	fresh water	Boron	kg	190	190	190
Output	fresh water	Bromate	kg	0	0	0
Output	fresh water	Bromine	kg	1,870	1,870	1,870
Output	fresh water	Calcium	kg	0.67	0.67	0.67

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	fresh water	Carbon disulphide	kg	0	0	0
Output	fresh water	Carbonate	kg	4.9E-04	4.9E-04	4.9E-04
Output	fresh water	Chlorate	kg	0	0	0
Output	fresh water	Chloride	kg	0.16	0.16	0.16
Output	fresh water	Chlorine, dissolved	kg	3.7E-04	3.7E-04	3.7E-04
Output	fresh water	Chromium	kg	0.011	0.011	0.011
Output	fresh water	Copper	kg	0.0098	0.0098	0.0098
Output	fresh water	DOC	kg	1.41	1.41	1.41
Output	fresh water	Fluoride	kg	32,600	32,600	32,600
Output	fresh water	Heavy metals	kg	0.019	0.019	0.019
Output	fresh water	Iron	kg	0.011	0.011	0.011
Output	fresh water	Lead	kg	0.0028	0.0028	0.0028
Output	fresh water	Magnesium	kg	0.052	0.052	0.052
Output	fresh water	Manganese	kg	0.0010	0.0010	0.0010
Output	fresh water	Nitrate	kg	15,100	15,100	15,100
Output	fresh water	Nitrogen	kg	0	0	0
Output	fresh water	Nitrogen, organic bounded	kg	1.5E-04	1.5E-04	1.5E-04
Output	fresh water	Particles	kg	0.034	0.034	0.034
Output	fresh water	Phosphate	kg	481	481	481
Output	fresh water	Phosphorus	kg	0	0	0
Output	fresh water	Potassium	kg	366,000	366,000	366,000
Output	fresh water	Sodium	kg	338,000	338,000	338,000
Output	fresh water	Sodium hypochlorite	kg	0	0	0
Output	fresh water	Sodium sulphate	kg	0	0	0
Output	fresh water	Solids, suspended	kg	3.37	3.37	3.37
Output	fresh water	Strontium	kg	0	0	0
Output	fresh water	Sulphate	kg	316,000	316,000	316,000

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	fresh water	Sulphide	kg	0	0	0
Output	fresh water	Tin	kg	0.0010	0.0010	0.0010
Output	fresh water	TOC	kg	1.41	1.41	1.41
Output	fresh water	Vanadium	kg	0.0020	0.0020	0.0020
Output	fresh water	Zinc	kg	0.023	0.023	0.023
Output	product	Char	kg	200	200	200
Output	product	Diesel	L	30.3	30.3	30.3
Output	product	Gasoline	L	30.3	252	363
Output	product	Hydrogen	L	23.3	23.3	23.3
Output	product	Residue	kg	448	448	448
Output	product	Gases	kg	147	147	147
Output	product	Liquid (Naphtha, light fraction)	MJ	265	265	265
Output	sea water	Inorganic emissions	kg	0.030	0.030	0.030
Output	sea water	Organic emissions	kg	0.0011	0.0011	0.0011
Output	sea water	Other emissions	kg	1,560	1,560	1,560
Output	sea water	Particles	kg	0.0037	0.0037	0.0037
Output	waste	Sand	kg	76.0	76.0	76.0
Output	waste	Wax	kg	46.0	46.0	46.0
Output	water	Wastewater	L	472	472	472

DOC,; GHG, greenhouse gas; n/a, not applicable; non-methane volatile organic compounds (NMOC), PM (particulate matter); TOC (total organic carbon); DOC (dissolved organic compounds)

Attachment E:
Gasification Life Cycle Inventory Data Compiled from the Literature

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Input	n/a	Aggregate	kg	3.36	19.6	35.8
Input	n/a	Aluminium	kg	0.0050	0.0095	0.014
Input	n/a	Chromium	kg	0.0015	0.0058	0.010
Input	n/a	Clay	kg	0.020	4.28	12.3
Input	n/a	Copper	kg	0.0031	0.0095	0.016
Input	n/a	Electricity	MJ	0.11	727	1,221
Input	n/a	Fossil energy	kg	0.0014	3.00	9.00
Input	n/a	Hydrogen	kg	11.0	11.0	11.0
Input	n/a	Iron	kg	0.044	0.11	0.18
Input	n/a	Limestone, calcium carbonate	kg	53.0	61.6	70.2
Input	n/a	Manganese	kg	0	0.0012	0.0025
Input	n/a	Nickel	kg	0.0027	0.013	0.024
Input	n/a	Pyrite	kg	0	0.095	0.19
Input	n/a	Rock	kg	105	165	225
Input	n/a	Sand	kg	0.049	7.47	14.9
Input	n/a	Sodium chloride	kg	11.0	43.0	74.9
Input	n/a	Soil	kg	1.18	1.52	1.85
Input	n/a	Steam	MJ	112	112	112
Input	n/a	Water	kg	8,780	69,890	131,000
Input	n/a	Zinc	kg	0	0.0019	0.0039
Input	n/a	Natural gas	MJ	4,620	4,620	4,620
Input	n/a	Calcium carbonate	kg	1.00	3.81	6.61
Input	n/a	Solid waste	m3	0.040	0.040	0.040
Input	n/a	Land use	m2	0.20	0.20	0.20
Input	n/a	Urea	kg	4.60	4.60	4.60
Input	n/a	Hydrated lime	kg	6.50	6.50	6.50
Input	n/a	Activated carbon	kg	0.50	0.50	0.50

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Input	n/a	Coke	kg	49.0	49.0	49.0
Input	n/a	Steel	kg	6.97	6.97	6.97
Input	n/a	Alkyd paint	kg	0.080	0.080	0.080
Input	n/a	Wood	m3	0.0030	0.0030	0.0030
Input	n/a	LDPE	kg	0.30	0.30	0.30
Input	n/a	Gravel	kg	0.39	0.39	0.39
Input	n/a	Brick	kg	0.46	0.46	0.46
Input	n/a	Cement	kg	0.040	0.040	0.040
Input	n/a	Anhydrite	kg	0.080	0.080	0.080
Input	n/a	Plaster	kg	0.11	0.11	0.11
Output	(blank)	Calcium chloride	kg	4.10	4.10	4.10
Output	(blank)	Residue	kg	66.0	66.0	66.0
Output	(blank)	Hydrogen chloride	kg	5.00	5.00	5.00
Output	air	Aluminium	kg	4.0E-04	4.0E-04	4.0E-04
Output	air	Ammonia	kg	0	0	0
Output	air	Argon	kg	0	5.15	10.3
Output	air	Carbon dioxide	kg	7.18	666	1,000
Output	air	Carbon monoxide	kg	0.022	0.53	1.46
Output	air	Copper	kg	1.1E-05	1.1E-05	1.1E-05
Output	air	Hydrocarbons, unspecified	kg	7.2E-05	7.8E-05	8.3E-05
Output	air	Hydrogen	kg	0	0.11	0.23
Output	air	Hydrogen sulphide	kg	0	0.0079	0.016
Output	air	Iron	kg	4.3E-05	8.8E-05	1.3E-04
Output	air	Lead	kg	9.1E-06	9.2E-05	2.4E-04
Output	air	Manganese	kg	8.5E-06	1.7E-05	2.6E-05
Output	air	Mercury	kg	3.4E-06	3.7E-05	7.0E-05
Output	air	Methane	kg	0.51	0.95	1.38

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	air	Methane, biogenic	kg	7.8E-05	2.4E-04	4.0E-04
Output	air	Nickel	kg	4.2E-06	2.3E-05	4.0E-05
Output	air	Nitrogen	kg	3,180	3,180	3,180
Output	air	Nitrogen monoxide	kg	0	0	0
Output	air	Nitrogen oxides	kg	0.074	0.37	0.78
Output	air	Nitrogen, atmospheric	kg	0	0	0
Output	air	Nitrogentriflouride	kg	0	0.10	0.20
Output	air	Nitrous oxide	kg	0	0	0
Output	air	NMVOC	kg	0.019	0.020	0.020
Output	air	Oxygen	kg	0.56	262	674
Output	air	Particles	kg	0.0035	0.019	0.038
Output	air	Selenium	kg	6.2E-06	9.0E-06	1.2E-05
Output	air	Sulphur	kg	0	0.31	0.62
Output	air	Sulphur dioxide	kg	0.012	0.18	0.43
Output	air	Tin	kg	5.5E-06	7.3E-06	9.1E-06
Output	air	Titanium	kg	2.5E-06	5.3E-06	8.1E-06
Output	air	Vanadium	kg	8.8E-06	3.5E-05	6.2E-05
Output	air	VOC, unspecified	kg	0	0.0028	0.011
Output	air	Zinc	kg	1.6E-05	1.3E-04	3.3E-04
Output	air	Hydrogen chloride	kg	0.032	0.032	0.032
Output	air	Nitrogen (atmospheric)	kg	3,700	3,700	3,700
Output	air	Carbon dioxide, biogenic	kg	618	618	618
Output	air	Carbon dioxide, fossil	kg	612	612	612
Output	air	Cadmium	kg	6.0E-06	6.5E-06	6.9E-06
Output	air	Hydroflouric acid	kg	8.4E-04	8.4E-04	8.4E-04
Output	air	Hydrochloric acid	kg	0.013	0.013	0.013
Output	air	Dioxins and furans	kg	3.1E-12	2.6E-11	4.8E-11

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	air	Hydrogen flouride	kg	3.4E-04	3.4E-04	3.4E-04
Output	air	Arsenic	kg	6.0E-05	6.0E-05	6.0E-05
Output	air	PCBs	kg	0	0	0
Output	fresh water	Aluminium	kg	0.018	1.16	2.30
Output	fresh water	Ammonia	kg	0	1.3E-04	2.6E-04
Output	fresh water	Ammonium	kg	1.1E-04	0.0017	0.0033
Output	fresh water	Antimony	kg	0	0.027	0.054
Output	fresh water	Barium	kg	0	0	0
Output	fresh water	BOD	kg	0.0020	1.83	3.66
Output	fresh water	Boron	kg	216	222	227
Output	fresh water	Bromate	kg	0	4.2E-04	8.4E-04
Output	fresh water	Bromine	kg	0	2,910	5,820
Output	fresh water	Calcium	kg	0.87	1.46	2.05
Output	fresh water	Carbon disulphide	kg	0	0	0
Output	fresh water	Carbonate	kg	7.2E-04	0.0010	0.0013
Output	fresh water	Chlorate	kg	0	0.0032	0.0064
Output	fresh water	Chloride	kg	498,000	4,239,000	7,980,000
Output	fresh water	Chlorine, dissolved	kg	4.5E-04	6.1E-04	7.7E-04
Output	fresh water	Chromium	kg	0	0.017	0.035
Output	fresh water	Copper	kg	0	0.015	0.031
Output	fresh water	DOC	kg	0.0025	2.10	4.20
Output	fresh water	Fluoride	kg	46,400	56,650	66,900
Output	fresh water	Heavy metals	kg	0.022	0.042	0.061
Output	fresh water	Iron	kg	0	0.017	0.033
Output	fresh water	Lead	kg	0	4.19	8.38
Output	fresh water	Magnesium	kg	0.098	0.13	0.15
Output	fresh water	Manganese	kg	0.0029	0.0053	0.0078

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	fresh water	Nitrate	kg	2,230	6,865	11,500
Output	fresh water	Nitrogen	kg	0	1.2E-04	2.5E-04
Output	fresh water	Nitrogen, organic bounded	kg	2.3E-04	3.5E-04	4.6E-04
Output	fresh water	Particles	kg	0.063	0.14	0.22
Output	fresh water	Phosphate	kg	1,000	2,655	4,310
Output	fresh water	Phosphorus	kg	0	1.5E-04	3.0E-04
Output	fresh water	Potassium	kg	8,170	574,085	1,140,000
Output	fresh water	Sodium	kg	483,000	733,500	984,000
Output	fresh water	Sodium hypochlorite	kg	0	4.8E-04	9.6E-04
Output	fresh water	Sodium sulphate	kg	0	0.0036	0.0072
Output	fresh water	Solids, suspended	kg	0.19	5.34	10.5
Output	fresh water	Strontium	kg	0	0.0014	0.0028
Output	fresh water	Sulphate	kg	18.0	468,509	937,000
Output	fresh water	Sulphide	kg	0	1.9E-04	3.9E-04
Output	fresh water	Tin	kg	0	0.0016	0.0032
Output	fresh water	TOC	kg	0.0025	2.21	4.42
Output	fresh water	Vanadium	kg	0	0.0031	0.0062
Output	fresh water	Zinc	kg	1.7E-09	0.036	0.072
Output	product	Electricity	MJ	2,466	2,466	2,466
Output	product	Syncrude	kg	822	822	822
Output	product	Gases	kg	90.0	90.0	90.0
Output	sea water	Inorganic emissions	kg	0.046	0.073	0.099
Output	sea water	Organic emissions	kg	9.0E-04	9.9E-04	0.0011
Output	sea water	Other emissions	kg	2,010	2,280	2,550
Output	sea water	Particles	kg	0.0052	0.0079	0.011
Output	waste	Solid waste	kg	50.0	50.0	50.0
Output	soil	Residue	kg	120	120	120

Flow Type	Release Compartment	Material	Unit per tonne	Min of Sum of Quantity, Harmonized Units	Average of Sum of Quantity, Harmonized Units	Max of Sum of Quantity, Harmonized Units
Output	soil	Solid waste	kg	71.1	71.1	71.1
Avoided	n/a	Electricity	MJ	1,620	1,620	1,620
Reuse	n/a	Metals	kg	36.0	36.0	36.0
Reuse	n/a	Slag	kg	206	206	206

BOD, biological oxygen demand; DOC, dissolved organic compound; n/a, not applicable; TOC, total organic carbon

Attachment F:
Decision Makers Guide for Assessing Municipal Solid Waste Energy Recovery Technologies

Decision Makers Guide for Assessing Municipal Solid Waste Energy Recovery Technologies

Sustainable materials management (SMM) is a systemic approach to using and reusing materials more productively over their entire life cycles. It represents a change in how our society thinks about the use of natural resources and environmental protection. The United States Environmental Protection Agency (EPA) has established a Non-Hazardous Materials and Waste Management Hierarchy, which prioritizes and ranks the various management strategies from most to least environmentally preferred. The hierarchy places emphasis on reducing, reusing, and recycling as key to sustainable materials management. Some communities are also interested in assessing energy recovery alternatives for non-recyclable materials in municipal solid waste (MSW).

Current energy recovery from MSW in the US is primarily the result of landfill gas recovery and waste-to-energy (WTE) or refuse-derived energy (RDF) plants. New and emerging technologies for managing MSW are of interest and include anaerobic digestion, gasification and pyrolysis. These technologies are considered as "emerging" because they do not have the same level of operational experience or commercialization in the US as historically used technologies such as mass-burn WTE and landfill facilities. These technologies are also referred to as "conversion technologies" because they seek to convert portions of MSW into energy and/or commodity products via thermal, chemical, and/or biological processes.

Conversion technologies can help to advance EPA's SMM goals and provide economic opportunities and environmental benefits to your community. However, these technologies are complex systems that will require significant capital investment and a robust supporting environment (e.g., policies, new market development) to ensure the technology is successful and sustainable. Implementing a new conversion technology may also entail changes that align collection and sorting infrastructure and procedures to the provide specific feedstock requirements for the facility.

As with any proposed MSW management strategy or technology, it is important to ask questions and to complete a thorough evaluation of these emerging conversion technologies. The purpose of this guide is to provide a structured approach for evaluating MSW energy recovery technologies to help community leaders make informed decisions on the potential solutions to managing waste that best meets the needs and goals of their communities. Planning and decision making among alternative waste management technology options is complex, but we can approach it in five steps:

Step 1 Define your MSW management and sustainability goals

Well-defined and meaningful goals serve as a guide for navigating varied and complex options for how best to manage waste within your community. EPA's waste management hierarchy provides a strong starting point when setting goals for it ranks waste management strategies from the most to least environmentally preferred. The hierarchy prioritizes source reduction and reuse, recycling, and composting. Many communities have already established goals related to sustainability and waste management, typically in strategic planning documents such as environmental plans, zero waste plans, or integrated waste management plans. As a first step, review existing goals and consider whether they are relevant and meaningful, or need to be revised.

Key goals questions to ask

- What are the current MSW management goals and policies?
- What are the broader community sustainability (e.g., LEED [Leadership in Energy and Environmental Design]) goals and policies?
- How does energy recovery from MSW advance these goals and policies?

Step 2 Understand your available MSW feedstock

MSW energy recovery technologies have different requirements (or constraints) for feedstock quantity and composition. To identify energy recovery technologies that are best suited to your community's MSW feedstock, it is important to understand the types and amounts of MSW that are generated by your community and that are available. Many communities have performed waste characterization studies. With respect to energy recovery technologies, it will be particularly important to understand the detailed types (e.g., organic or plastic materials types rather than bulk mixed amounts) and amounts of post-recycled material available.

Key feedstock questions to ask

- What is the quantity and composition of post-recycled MSW available?
- How is the MSW currently collected and processed (i.e., sorted)?
- Who currently controls the waste and for how long?

Step 3 Identify suitable energy recovery technology options

The suitability of any energy recovery technology will depend on the quantity and composition of available feedstock and the manner in which it has been collected—that is, is it a mixture of materials or source segregated. Landfill and WTE facilities typically accept unprocessed MSW or residuals from other recycling or treatment processes. Advanced energy recovery technologies—such as AD, gasification and pyrolysis—typically accept only certain materials and/or have feedstock preprocessing requirements. These preprocessing requirements can include sorting, size reduction, washing and drying. In general, gasification can accept minimally processed MSW whereas pyrolysis and AD will require more robust separation and/or processing as their accepted materials can be more limited. Any preprocessing can occur as part of collection and separation (e.g., MRF [materials recovery facility]) system and/or as a part of the energy recovery technology. Figures 1 to 3 illustrate possible management pathways for different types of MSW feedstock: unsegregated MSW, food waste and plastic waste.

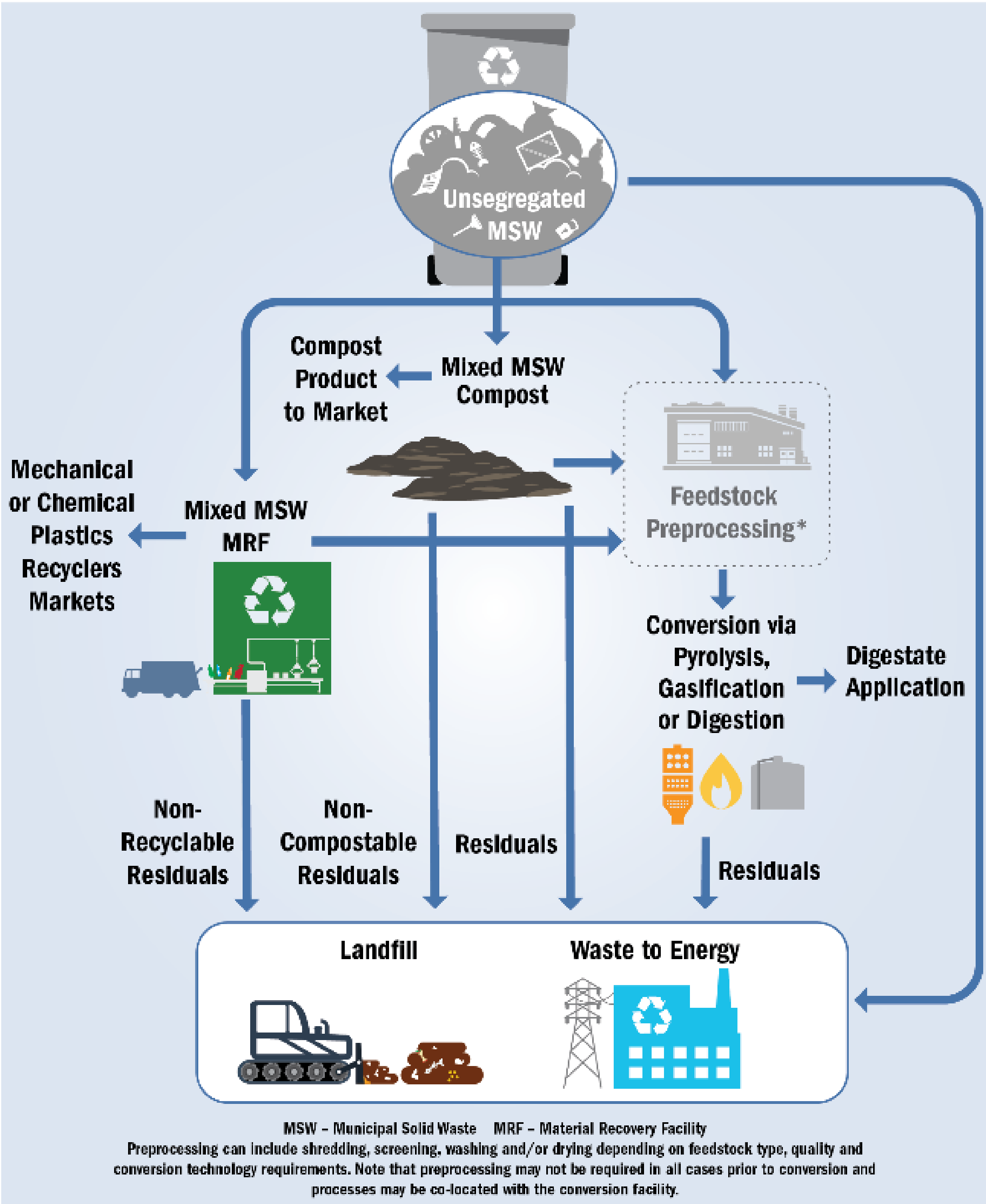


Figure 1. Technology pathways unsegregated MSW.

Note: Although technically feasible to compost mixed MSW feedstock, there are no known operating MSW compost facilities in the US probably due to the heterogeneity of the MSW feedstock. This approach has been tried and not found to be successful.

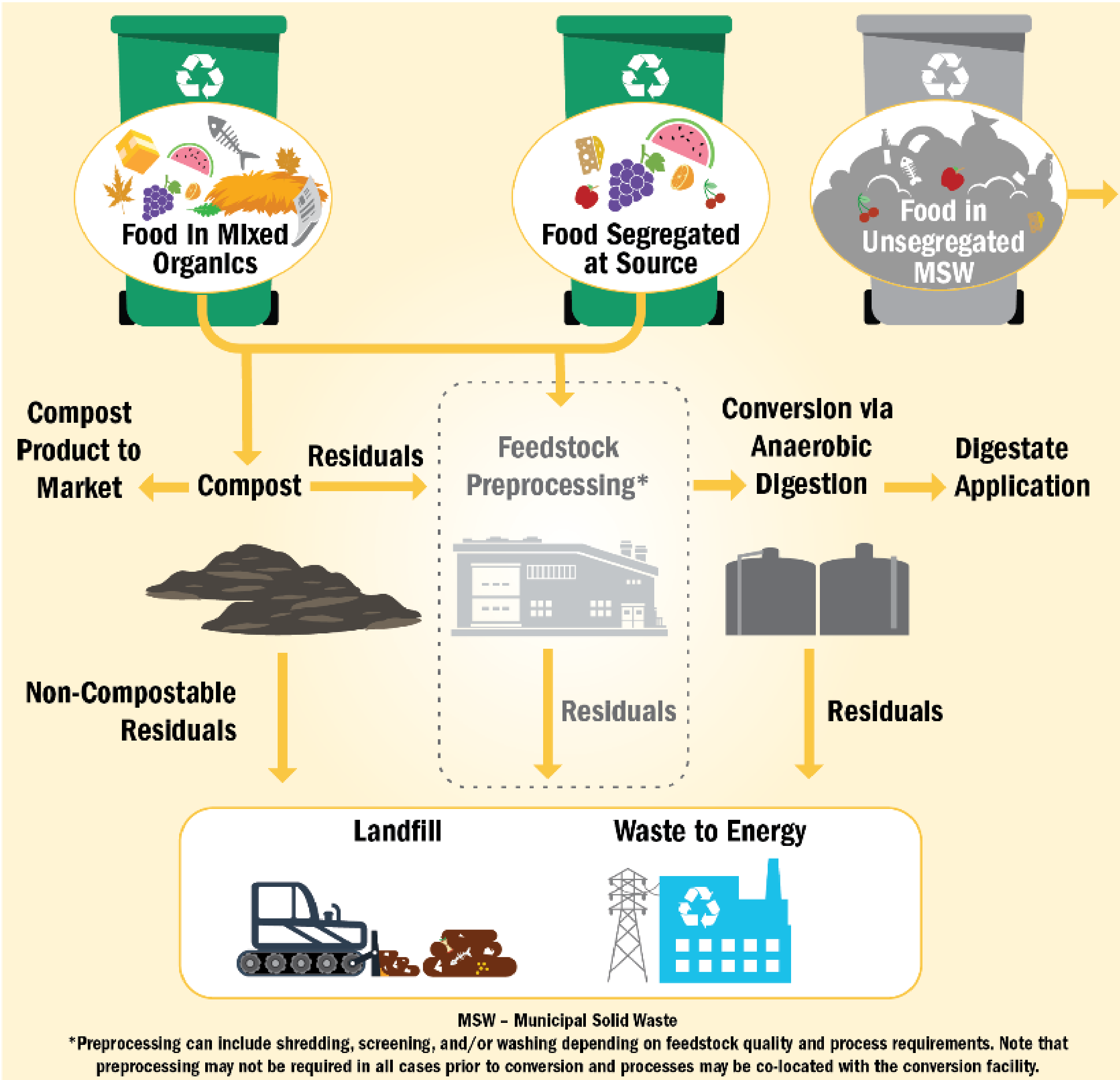


Figure 2. Pathways for food waste.

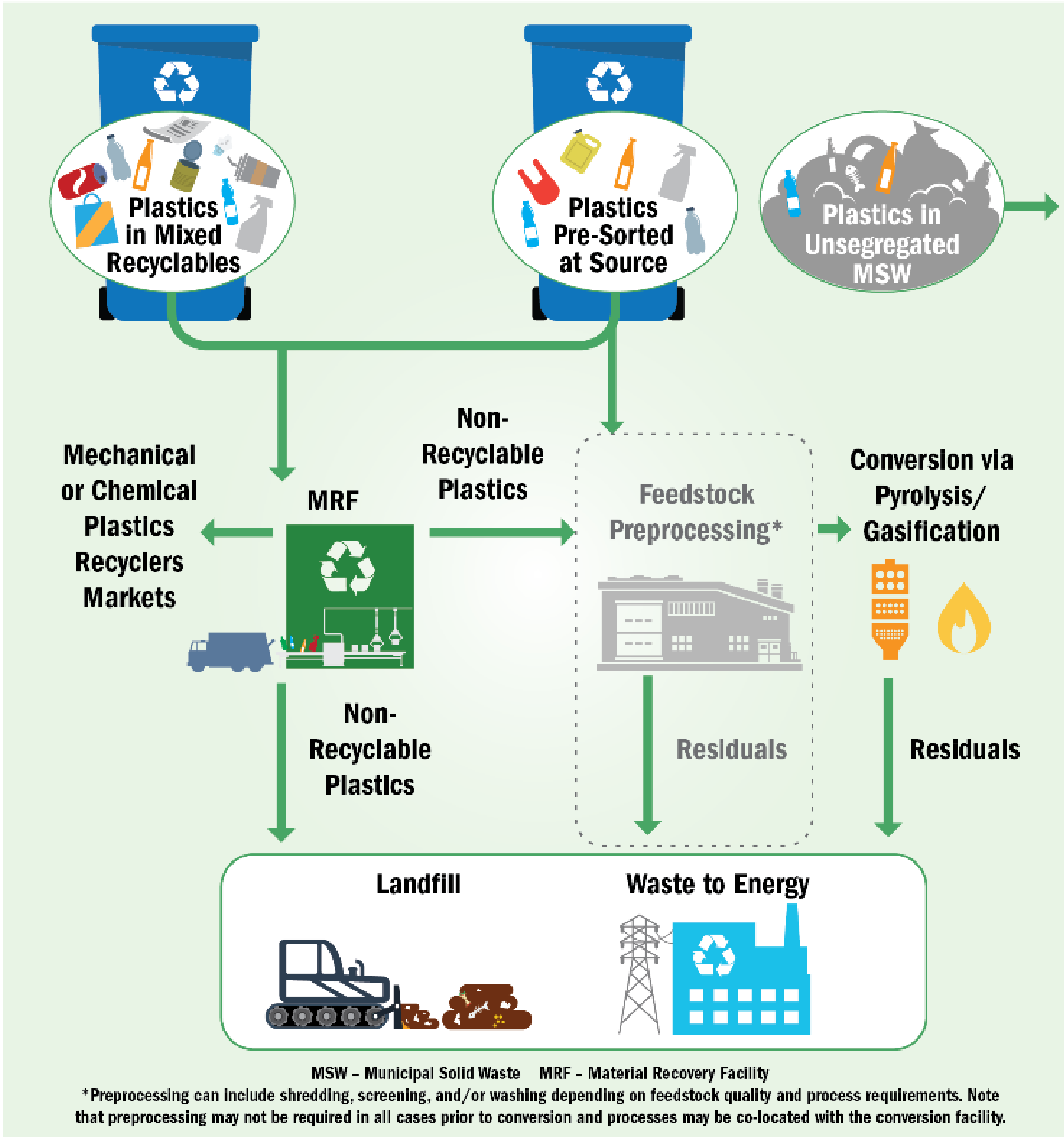
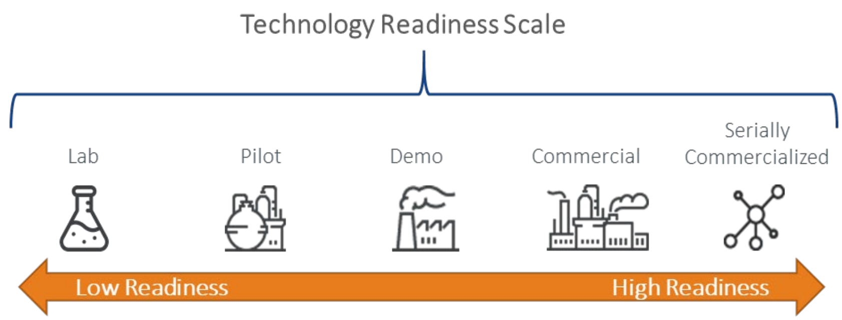


Figure 3. Pathways for plastic waste.



Descriptions and key characteristics for MSW energy recovery technologies are presented in **Attachment A**. These technologies differ in terms of their "readiness." Landfill and WTE are well established options. AD has grown rapidly in recent years with currently more than 25 stand-alone facilities that accept multi-source facilities that process food and other organic fractions of MSW. There are a number of gasification and pyrolysis technologies in various stages of research and development. However, there are currently only one gasification and two pyrolysis facilities operating at a commercial scale in the US using fractions of MSW as feedstock.

In additional to consideration of what technology is most suitable to your available feedstock and the readiness of the technologies, it is important to consider what the primary end product (e.g., electrical energy, liquid fuel, biogas) is from each technology option. Community needs and market viability for these end products will differ by location.

Key technology questions to ask

- What are the accepted feedstocks and any preprocessing requirements of the technology?
- What are the minimum and maximum capacities of the technology?
- What is the main energy product generated by the technology?
- What is the technical readiness of the technology?

Step 4 Evaluate the cost and benefits for technology options

Cost associated with energy recover from MSW will vary by technology and region. Tipping fees for landfills[89] and WTE[90] plants are readily available with landfills tipping fees ranging from $30 to $155 per ton and WTE ranging from $65-75 per ton in the US. Cost and/or tipping fee data for newer AD, gasification and pyrolysis technologies is limited and often anecdotal. Ultimately, the cost will be location specific and depend on multiple factors such as the specific technology facility costs, permitting, feedstock segregation and processing, operational costs, market prices for products and disposal or management costs for residuals such as ash or digestate. A broader range of economic benefits may also include job creation and local economic development.

From an environmental perspective AD, gasification and pyrolysis are considered "energy recovery" and preferable to "treatment and disposal" on EPA's waste management hierarchy. However, the ability to draw life cycle environmental performance conclusions between these newer technologies and conventional energy recovery via WTE and landfill gas recovery is limited due to the general lack of newer technology operational history, experience and available long term data (more than 5 years) to establish environmental performance over time.

All energy recovery technology options will generate gaseous, liquid and solid emissions that require additional treatment or disposal. The literature data suggest that gasification and pyrolysis can result in carbon equivalent emissions comparable to WTE and landfills (see US EPA, 2020). This is due to the carbon emissions associated with the combustion of the syngas or synfuel product, which is considered, or partially considered, to be fossil-

[89] https://erefdn.org/product/analysis-msw-landfill-tipping-fees-2/
[90] https://www.usi.edu/recycle/solid-waste-landfill-facts/

based fuel. Conversely, the use of biogenic (i.e., organic) feedstock in either conventional or conversion technologies will result in a biogenic energy product that is considered carbon neutral. For example, AD of food waste will create biogenic energy that is considered carbon neutral. Likewise, landfills also produce biogenic energy and the organic fraction of waste combusted in a WTE plant (or gasification or pyrolysis) is considered biogenic with respect to carbon accounting.

All energy recovery technologies produce solid residuals that sometimes include hazardous waste streams (e.g., ash, char, wax, slag, and digestate) and will require additional treatment via combustion or disposal in solid or hazardous waste landfill. Technology process by-products may also require treatment or disposal if a viable end-use or market cannot be found. The data available from the literature show that advanced energy recovery technologies of AD, gasification and pyrolysis will generally produce as much or higher amounts of residuals as conventional WTE, or approximately 5-15 percent of feedstock volume. The exact amounts of solid residuals generated will be dictated by the feedstock composition and the level of acceptable contamination by specific technology. In general, it could be expected that a mixed feedstock (e.g., bulk MSW, materials recovery facility [MRF] residuals) will generate greater amounts solid residuals than a source segregated feedstock (e.g., plastics, food waste).

Existing tools such as EPA's Municipal Solid Waste Decision Support Tool (MSW DST) can help to assess the cost and life-cycle environmental performance of MSW energy recovery options. Since AD, gasification and pyrolysis technologies are more emerging in nature, there is a general lack of operational history, experience and accompanying data. Some technology test and model estimated data is available from the literature and can be combined with the collection, processing and residuals treatment and disposal options in tools like the MSW DST to assess cost and environmental performance (see US EPA, 2020).

Key cost/benefit questions to ask

- What is the full cost and revenue potential for the technology?
- What are the local employment opportunities?
- What is the net energy balance for the technology?
- What would be the air and water emission levels and how would residual waste be managed?
- Does the technology have any significant resource requirements (e.g., water)?

Step 5 Identify best-fit technology options

Ultimately, identifying an energy recovery technology that is best matched to your specific community will take into account and align several factors including your community goals; quantify, type and availability of consistent feedstock; technology options and their suitability to available feedstock and technology readiness; technology product(s) type and local/regional needs and access to end markets; and cost and benefits.

In addition to the key questions in steps 1-4, other important questions to consider when making decisions about potential MSW energy recovery technologies can include:

- Geographic footprint (land requirement) and siting. Where would the facility be located and who would likely be impacted[91] by increased traffic, air emissions, noise, or odors?
- What level of public awareness and support is there for the technology?
- What are the relevant state and local regulations and laws, and is there a precedent for permitting the technology?
- What is the capacity of the local/regional government agencies to facilitate permitting and to monitor and enforce permit conditions?
- Is there a potential for infrastructure "lock in" (i.e., inability to change MSW management strategy or programs in the future)?

Additional Resources:

US EPA. 2020. *Assessment of Municipal Solid Waste Energy Conversion Technologies*. [Forthcoming]

SWANA & NWRA. 2017. *Briefing for Elected Officials Effective Responses to Emerging Waste Management Technology Proposals.* February 2017.

[91] Use EPA's EJSCREEN to identify minority and/or low-income populations, potential environmental quality issues, and areas where a combination of environmental and demographic indicators are greater than the norm.

Attachment A: Descriptions and key information for MSW energy recovery technologies.

Technology	Description	MSW Feedstocks Accepted	Primary Product and End Application(s)	Residual Requiring Disposal (by weight)	Number of Facilities Operating in the US
Anaerobic Digestion (AD)	AD plants use a controlled anaerobic environment (i.e., absent of added oxygen) to enhance the biochemical decomposition of organic matter by microorganisms to create biogas. The process does not require external heat. The biogas produced from an AD can be used directly, to generate electrical energy, or additionally treated to allow injection into the pipeline. Byproducts include air emissions, solid and/or liquid digestate. The solid and liquid digestate can be land applied, composted, used as a soil amendment or processed into fertilizer pellets. The liquid digestate can be further processed to concentrate nitrogen or phosphorous chemicals. These chemicals can be sold outright or added to fertilizers.	Food and yard waste	Biogas used to generate heat, electricity or fuels (e.g., CNG, LNG). Digestate can be used as fertilizer	Approximately 5-10%[a]	25+[92]
Gasification	Gasification plants use a thermal process that, in a controlled oxygen environment, convert organic or fossil fuel carbon-containing material into synthetic gas. The process is like pyrolysis, except that oxygen is added to maintain a reducing atmosphere in the reactor. Inert materials such as glass and metals are removed and then the feedstock is shredded to be a consistent size and fed into the gasifier. In the gasifier the materials are heated to temperatures of 1100 to 1800 degrees in a chamber with a controlled amount of oxygen resulting in a chemical reaction that produces syngas and residues. The syngas is cleaned to remove dust, ash, and tar and it may be further purified or conditioned. Char and ash may be reused (if approved for reuse) or will require disposal.	Carbon-containing materials in MSW	Synthetic gas used to generate electricity, heat, fuels, fertilizers and chemical products	Greater than 10%	2
Pyrolysis	Pyrolysis plants use heat to thermally decompose carbon-based material in the absence of oxygen. The main products of pyrolysis include gaseous products (syngas), liquid products (typically oils), and solids (char and any metals or minerals that might have been components of the feedstock). Pyrolysis plants generate synthetic oil which likely will require additional refining or cleaning to meet market requirements. Byproducts include petroleum wax and char. Wax produced (normally less than or equal to 10% by weight of feedstock) may be a marketable commodity. Char is considered a hazardous waste and approvals are often required for its disposal.	Plastics or biomass	Synthetic oil used to create fuel products or commodities (e.g., waxes)	Greater than 10%	4
RDF	RDF plants use mechanical systems to shred incoming MSW, separate out and recycle non-combustible materials, and produce a combustible mixture that is suitable as a fuel in a dedicated furnace or as a supplemental fuel in a conventional WTE plant. The RDF can either be used as-is (shredded fluff) or	MSW	Steam used to generate electricity or Combined Heat	Approximately 15-25%	13

[92] https://www.epa.gov/anaerobic-digestion/anaerobic-digestion-tools-and-resources#ADdata.

Technology	Description	MSW Feedstocks Accepted	Primary Product and End Application(s)	Residual Requiring Disposal (by weight)	Number of Facilities Operating in the US
	compressed into pellets, bricks, or logs for transportation, storage or sale. Like WTE, RDF facility combusts MSW in high heat, controlled conditions to produce steam from the boiler that is used to generate electricity or utilized in a combined heat and power system. It also produces combustion residues, or ash that will require disposal.		and Power (CHP)		
WTE	WTE plants use mass burn combustion to burn waste to generate heat and electricity. Mass burn combustion facilities take unsorted MSW – your trash – from bin to burner. The facility combusts MSW in high heat, controlled conditions to produce steam from the boiler that is used to generate electricity or utilized in a combined heat and power system. Ferrous metal is typically recovery from the ash and recycled. It also produces combustion residues, or ash that will require disposal. WTE facilities need a lot of feedstock. The smallest plant in the US has a capacity of 175 tons per a day.	MSW	Steam used to generate electricity or CHP	Approximately 15-25%	73[b]
Landfill with gas recovery	Landfills are large, outdoor engineered sites designed for the disposal of MSW and other wastes – the trash and garbage that is thrown away every day at home, work, and school. The design of landfills includes liners and other materials like clay to prevent groundwater contamination. Monitoring is required to determine if there is any groundwater contamination. Daily operation of landfills includes compacting and covering waste with several inches of soil or other cover material to reduce odor and litter as well as control rodents and pests. Landfills can also be designed to collect landfill gas and utilize this gas to generate energy products.	MSW	Biogas which can be used to generate heat, electricity and/or fuels (e.g., CNG, LNG)	0%	564[93]

AD, anaerobic digestion; CHP, combined heat and power; CNG, compressed natural gas; LNG, liquefied natural gas; MSW, municipal solid waste; RDF, refuse-derived fuel; WTE, waste-to-energy

[a]does not include digestate which typically is composted

[b]most existing WTE plants in the US have been operating for more than 20 years. Only one new WTE facility has been built in the US since 1995.

[93] https://www.epa.gov/lmop/landfill-gas-energy-project-data-and-landfill-technical-data

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